LArTPC Detector Capabilities

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Introduction

- I was asked to cover how the detector response and capabilities of LArTPCs can/will be understood with current/future initiatives.

- In other words, to summarize what is known about LArTPC detector performance, what we want to learn, and how this impacts present and future experiments.

- Things I won't cover in any detail since they'll be the focus of the next talks: **electronegative impurities** (Craig Thorn), **high-voltage** (Sarah Lockwitz), **photon detection** (Matt Toups), **electronics** (Veljko Radeka)

Introduction

To put it another way:

"When will we see performance plots from LArTPCs?"

- Question I was asked by a NuSTEC student last year.

- We have some information already from ICARUS (see A. Fava talk) and ArgoNeuT data, so I'll review selected topics from these.

- What other kinds of performance plots would we like to see from the experiments about to run (MicroBooNE, LArIAT, CAPTAIN), or those proposed to run in the future (Fermilab SBN, ELBNF)?

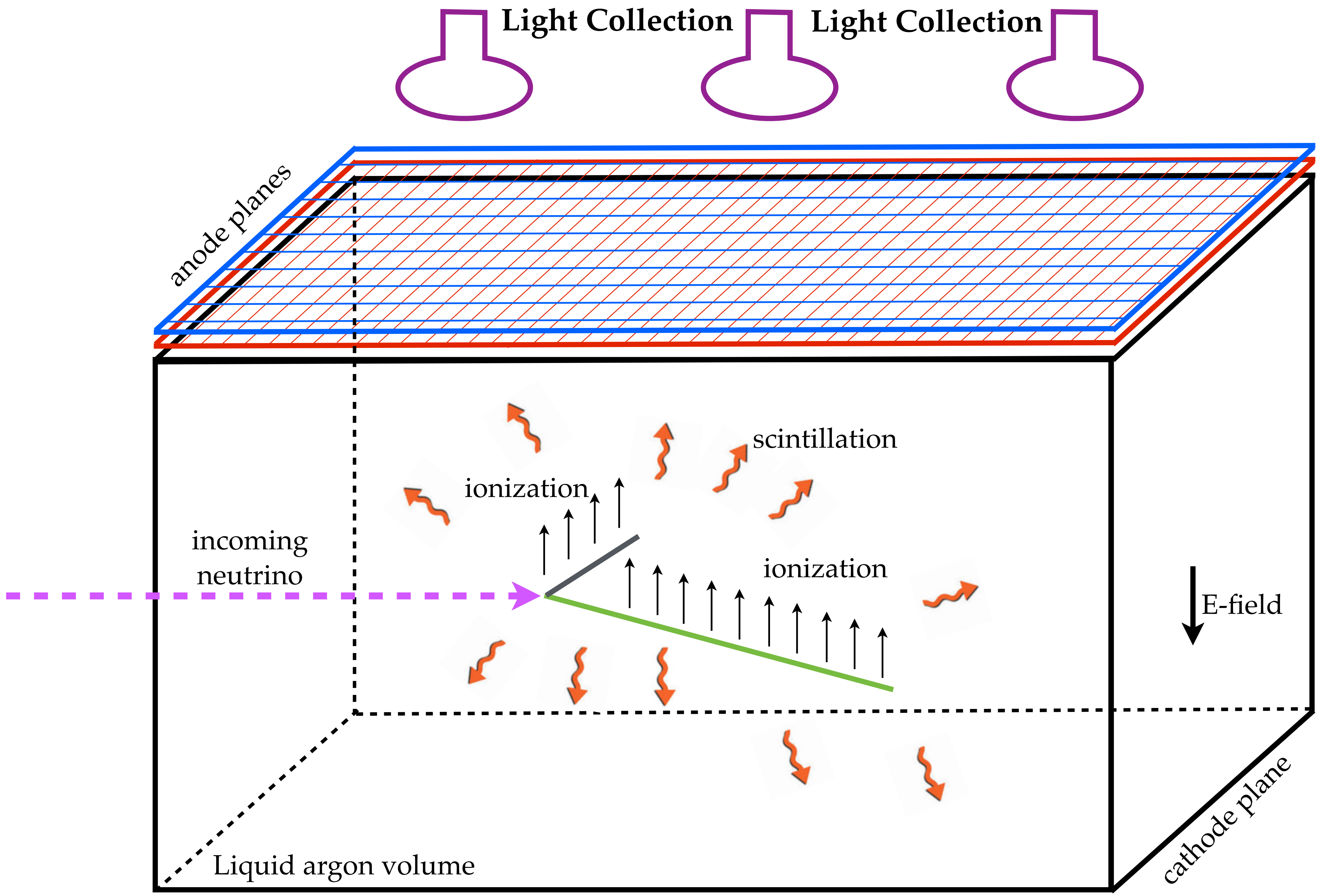
Detector Capabilities Topics

List of possible topics one could cover:

- Connecting deposited energy to measured signal
- Calorimetric precision
- Understanding em/hadronic showers
- Neutron response
- Particle identification
- Response to low-energy events
- Connections to current/future experiments

Liquid Argon Neutrino Detectors

Many design options to choose from…detector capability depends on these choices.

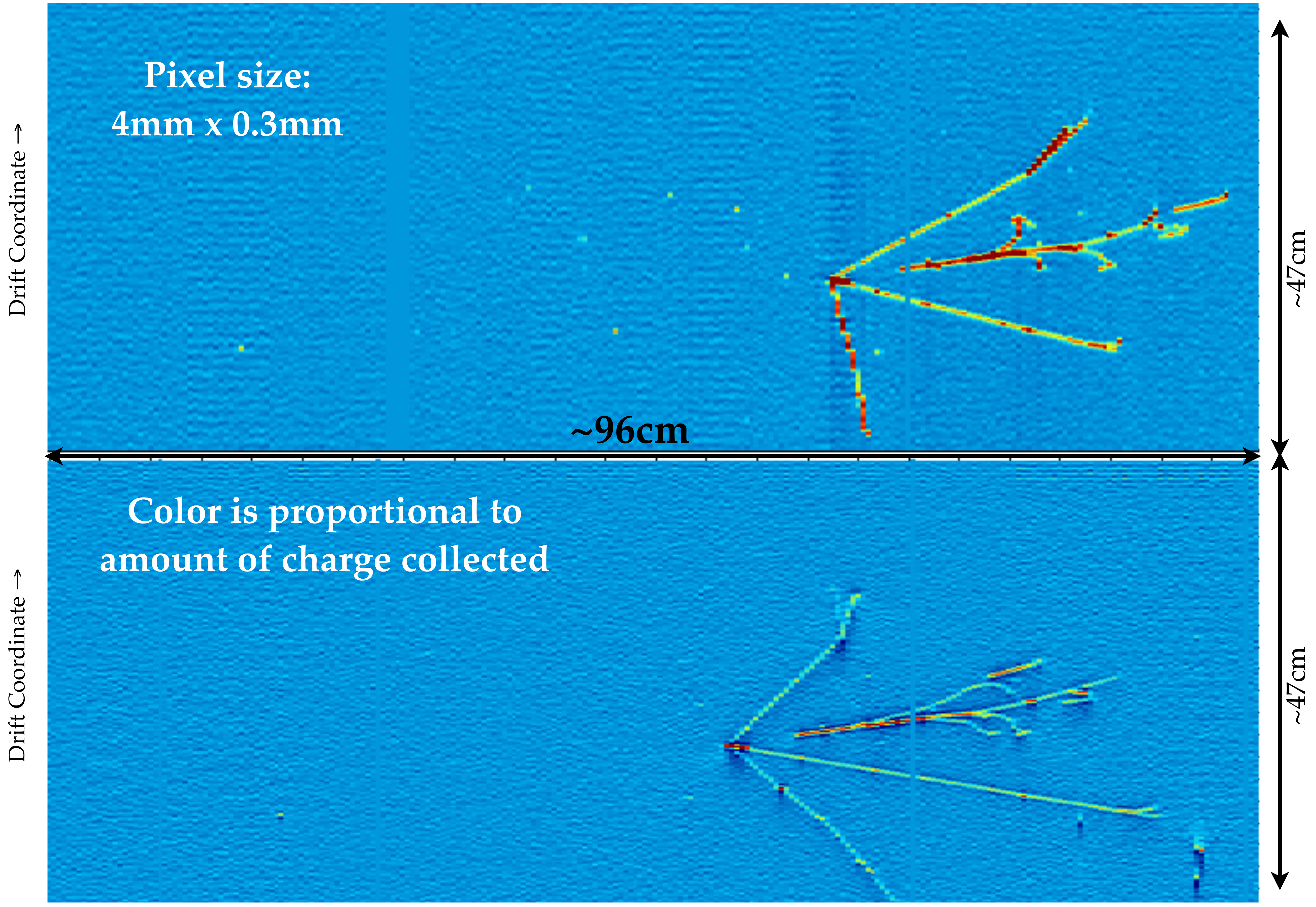


Refs:

1.) *Liquid-argon ionization chambers as total-absorption detectors*, W. Willis and V. Radeka, Nuclear Instruments and Methods 120 (1974), no. 2, 221-236.

2.) *The Liquid-argon time projection chamber: a new concept for Neutrino Detector*, C. Rubbia, CERN-EP/77-08 (1977)

Neutrino Interaction in ArgoNeuT



TPC Signal Development

- There is a great deal of ongoing hardware development for LArTPCs, which you'll hear more about in this session.
- Much of the current activity for LArTPCs revolves around developing robust reconstruction and simulation tools (*i.e.* extracting physics quantities from observed detector signals).
- The success and precision of current/future experiments is reliant on these tools, so it's important to gauge the performance of the tools through comparisons with data.

TPC Signal Development

- Ionization produced by charged-tracks creates a signal on TPC wires.
- The measured signal is the convolution of multiple physical processes.
- Try to model each process, in simulation and data-reconstruction.

Uber-function to represent LArTPC signal development

$$\mathcal{M} = \mathcal{R} \otimes \mathcal{I} \otimes \mathcal{D} \otimes \mathcal{F} \otimes \mathcal{E} \otimes \mathcal{G}$$

$\mathcal{R}$	Recombination
$\mathcal{I}$	Attachment to Impurities
$\mathcal{D}$	Diffusion
$\mathcal{F}$	Drift Field
$\mathcal{E}$	Electronics Shaping
$\mathcal{G}$	Geometrical Rotations

In an Ideal World…

- Apply the inverse of this uber-function to measured signal and recover the distribution of ionization in 3d x-y-z space (as a function of time), then proceed to apply reconstruction.

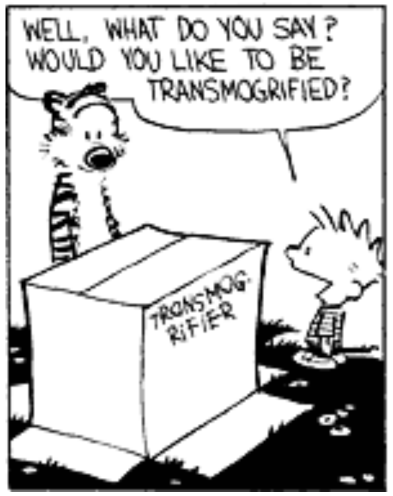
- In reality, we have no such reverse-transmogrification function, so we have been pursuing a variety of alternative approaches.

$\mathcal{S}(\mathrm{wire}, \mathrm{time})$ Signal measured on each wire as a function of time.

$\rho(\mathrm{x}, \mathrm{y}, \mathrm{z}, \mathrm{t})$ Distribution of ionization in TPC as a function of time,space.

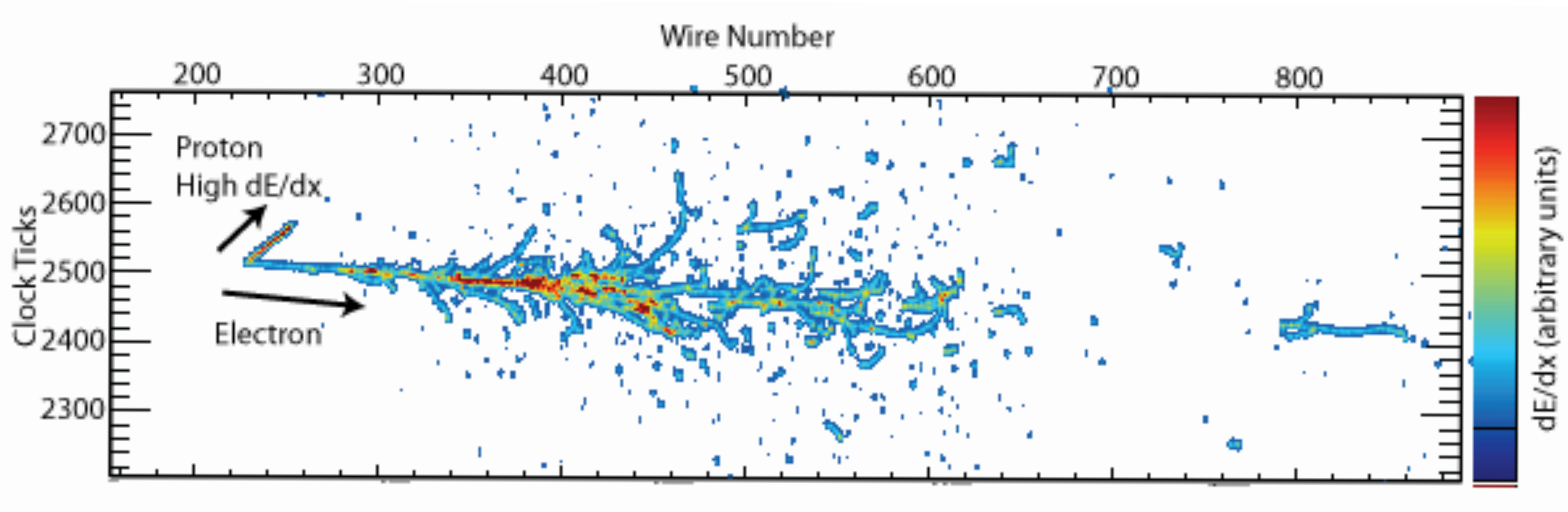
$$\mathcal{S} = \mathcal{M} \otimes \rho$$

$$\mathcal{M}^{-1}\mathcal{S} = \rho$$



Some Physics Motivations

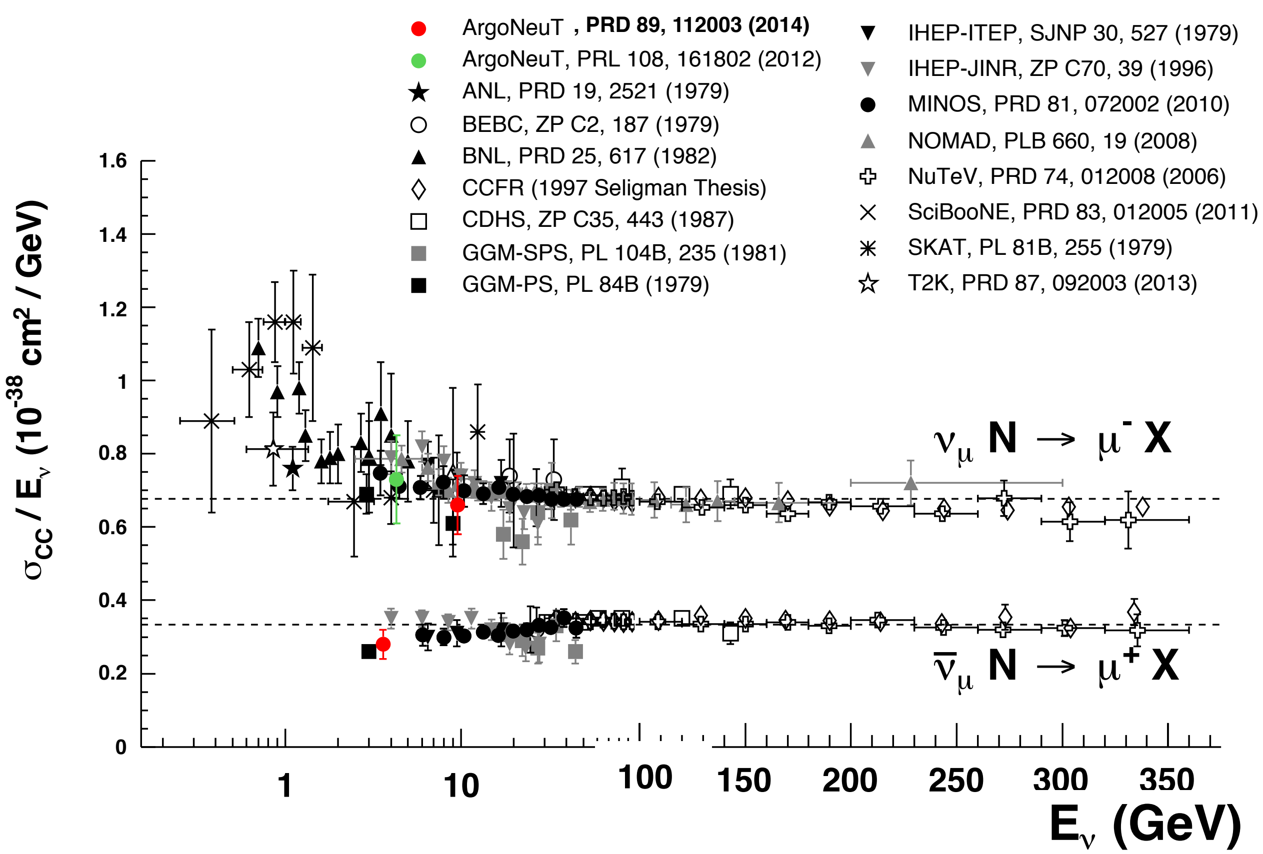
- Low Energy Neutrino Cross-Section Measurements: CC-inclusive, CCQE, NC π^o, etc…
- Measure things arising from use of nuclear target (multi-nucleon correlations, FSI, etc…)
- Study backgrounds relevant for Proton Decay searches in larger detectors (*e.g.* - Kaon production), and develop SuperNova analysis capabilities.
- Probe the Strange Quark content of Proton (*e.g.* - Δs, hyperon production, etc…)
- Be prepared for the unexpected.

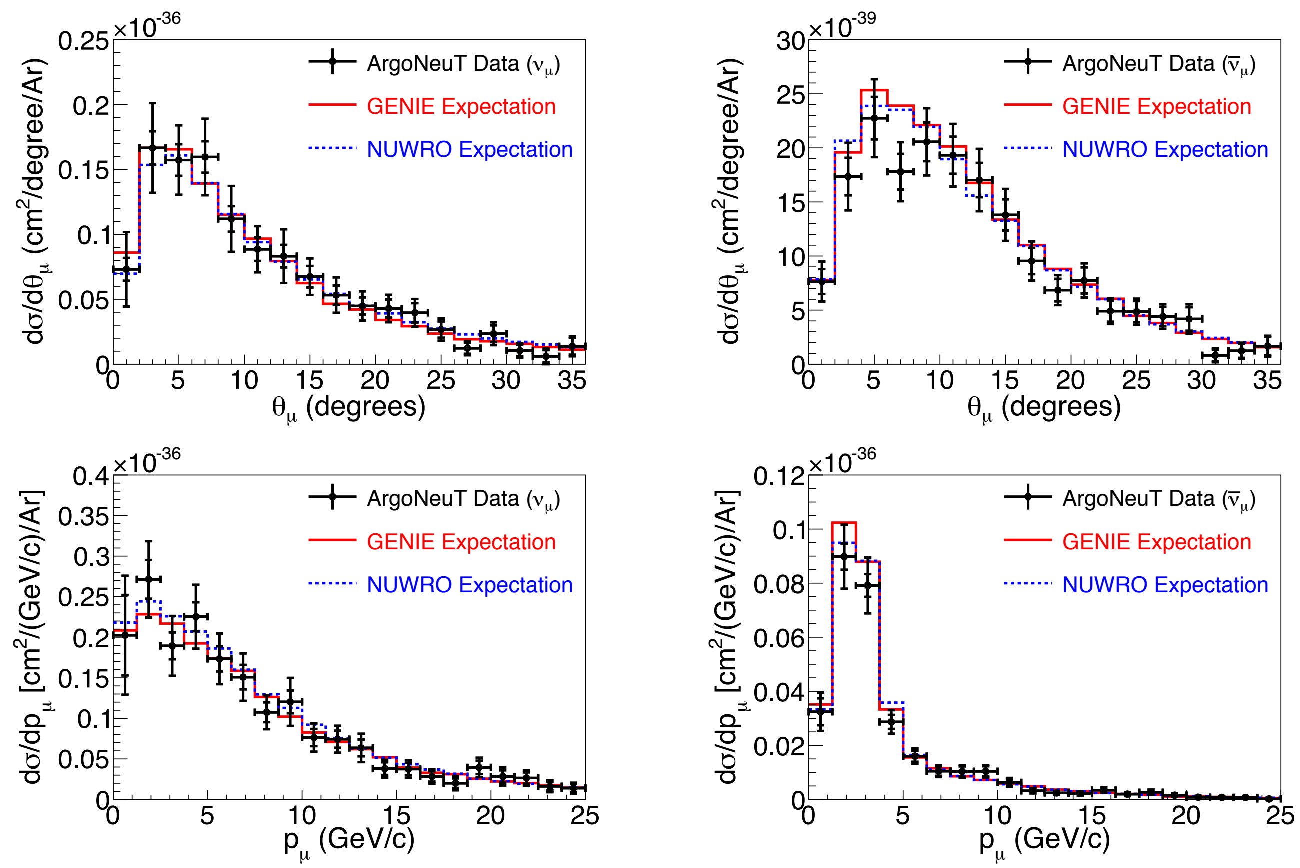


Example CCQE ν_e event simulated in MicroBooNE Collection Plane (zoomed in view)

Some Physics Motivations

- "Standard candle" measure of inclusive charged-current cross-sections have been performed using both antineutrinos and neutrinos. First time ever on argon target.
- MicroBooNE will have high-statistics necessary to do more refined things, like double-differential cross-sections (a la MiniBooNE).
- Measurements of muon momentum in a non-magnetized detector may come from multiple scattering, so proving the robustness of this technique is required.

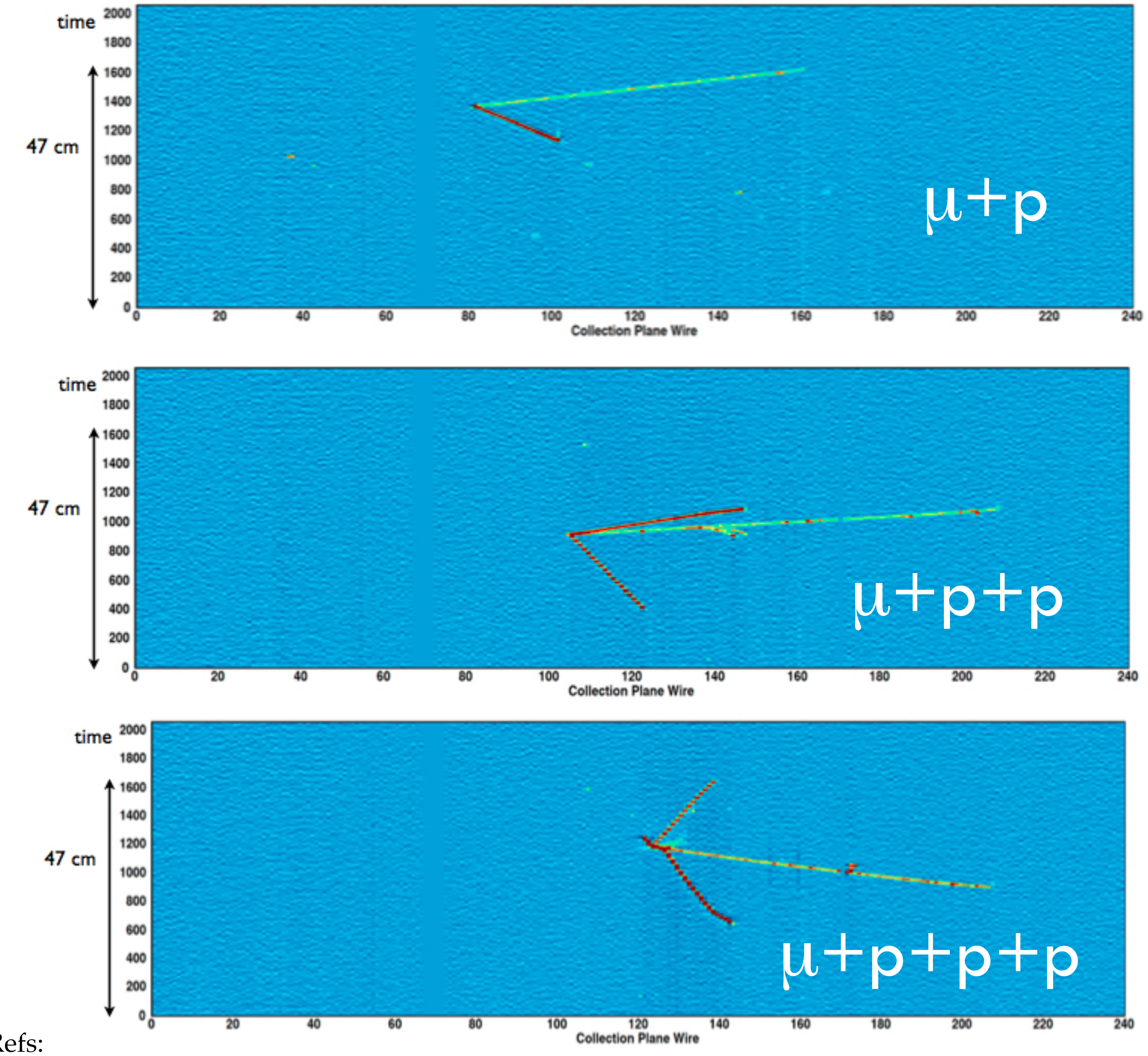


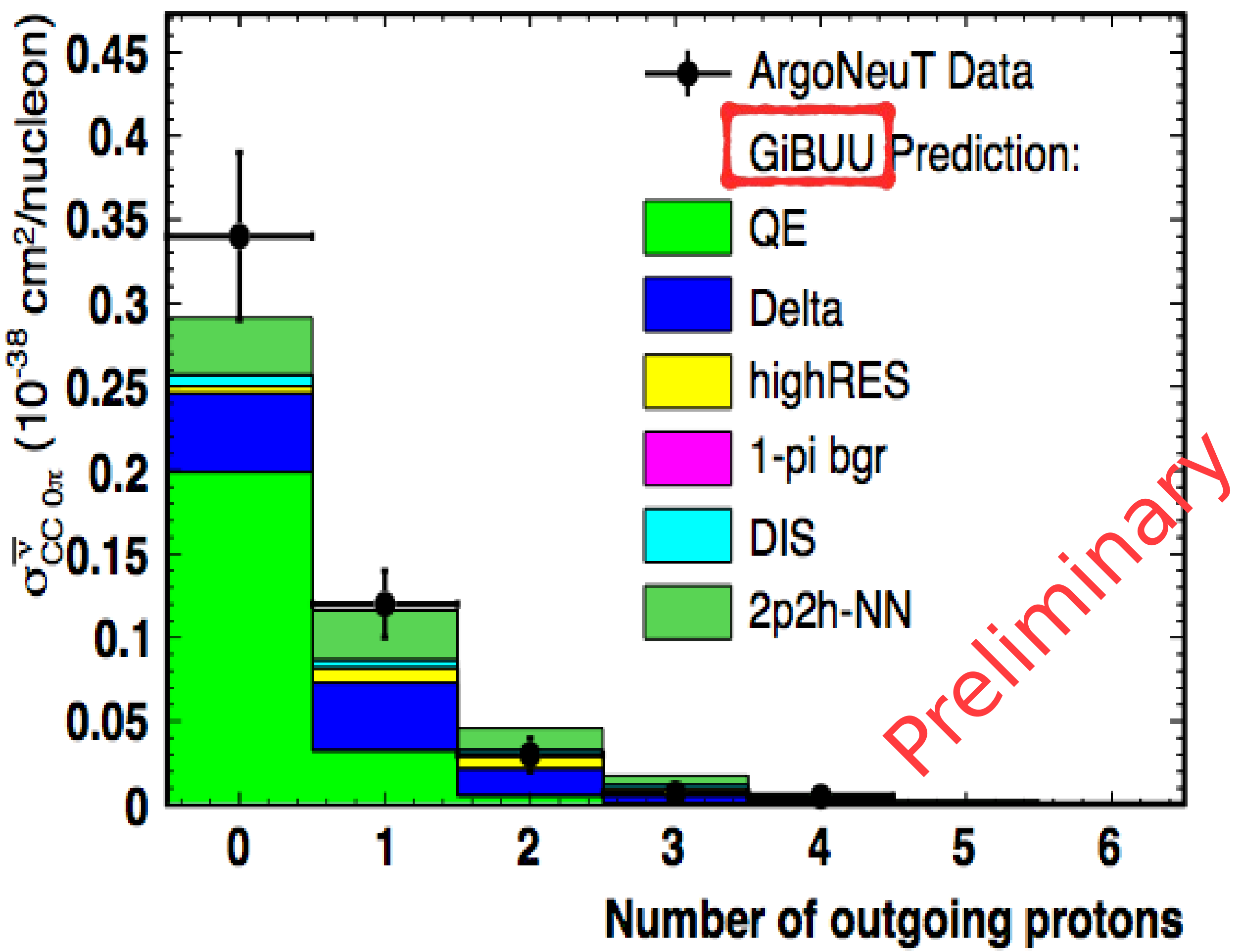


Refs:
1.) *First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon*, C. Anderson et al., PRL 108 (2012) 161802
2.) *Measurements of Inclusive Muon Neutrino and Antineutrino Charged Current Differential Cross Sections on Argon in the NuMI Antineutrino Beam*, R. Acciarri et al, PRD 89, 112003 (2014)

Some Physics Motivations

- Granularity of LArTPC opens up a window into nuclear physics (multi-nucleon correlations) that is:
  1. necessary to understand in the broader precision neutrino oscillation experimental program
  2. interesting to study due to the many rich connections to electron-scattering and nuclear theory
- Measuring quantities such as multiplicity of protons in charged-current events can be a useful method of testing nuclear models present in generators.



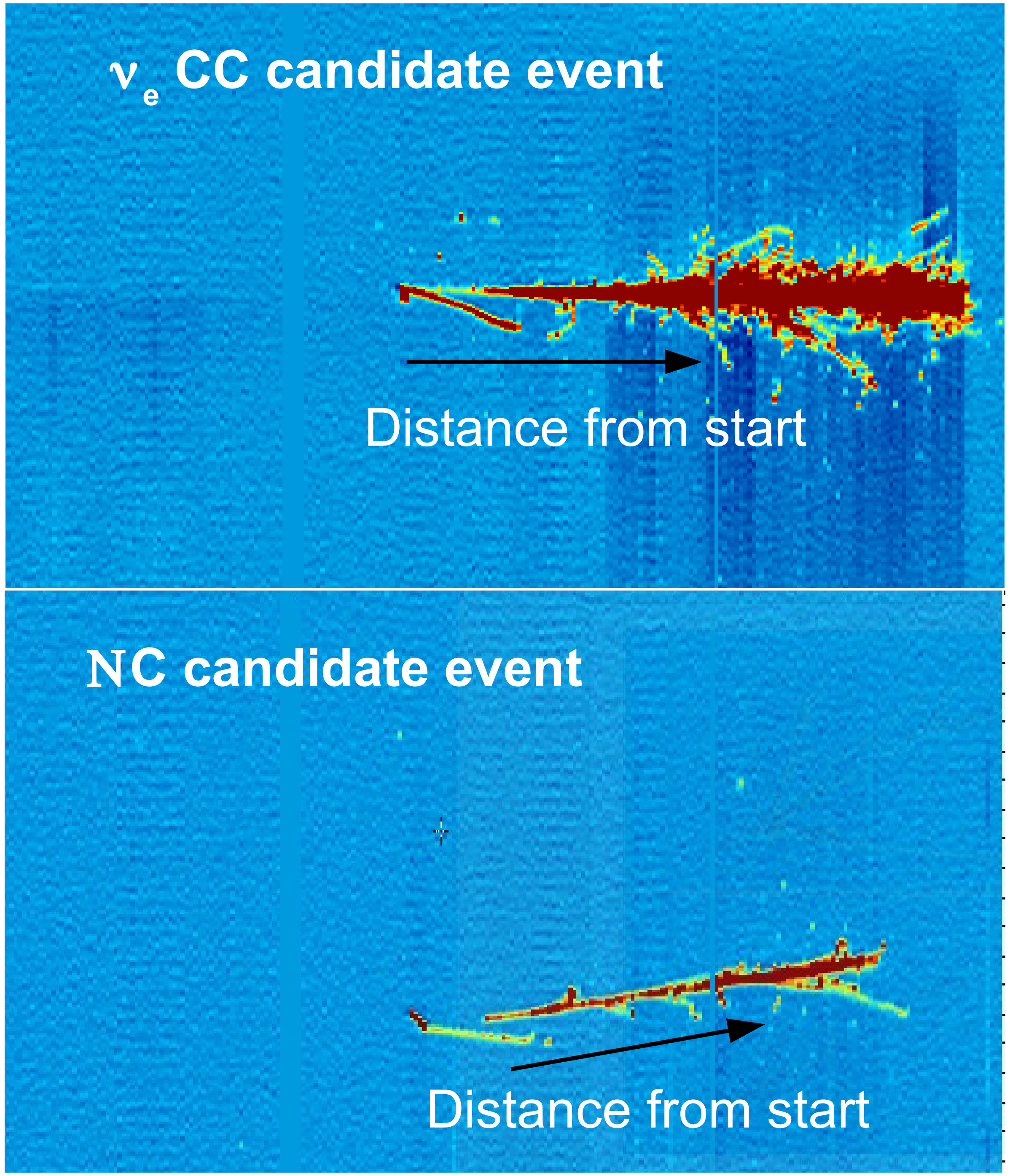


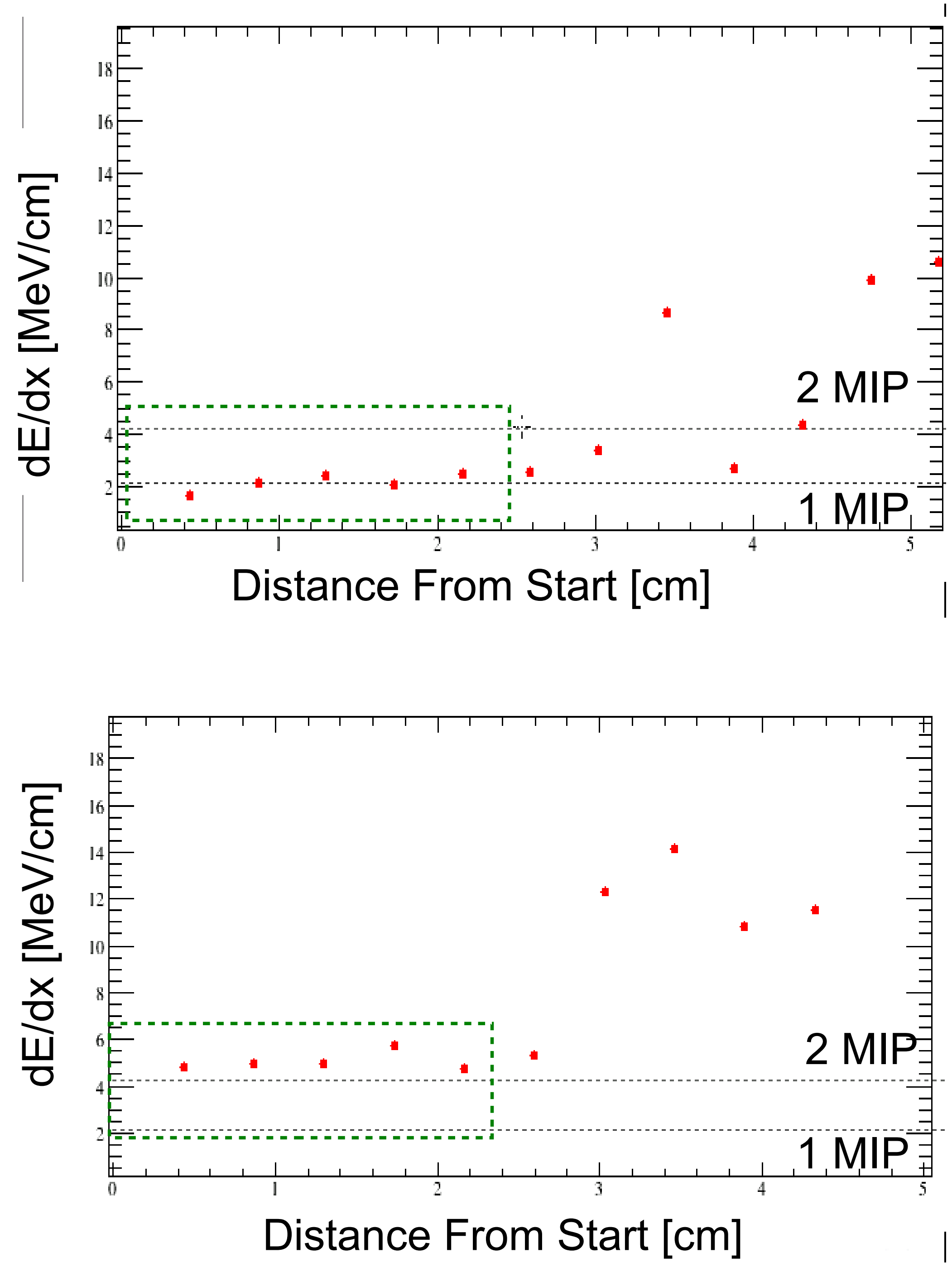
Refs:

1.) *The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam line*, R. Acciarri et al, Phys. Rev. D 90, 012008 (2014)

Particle Identification

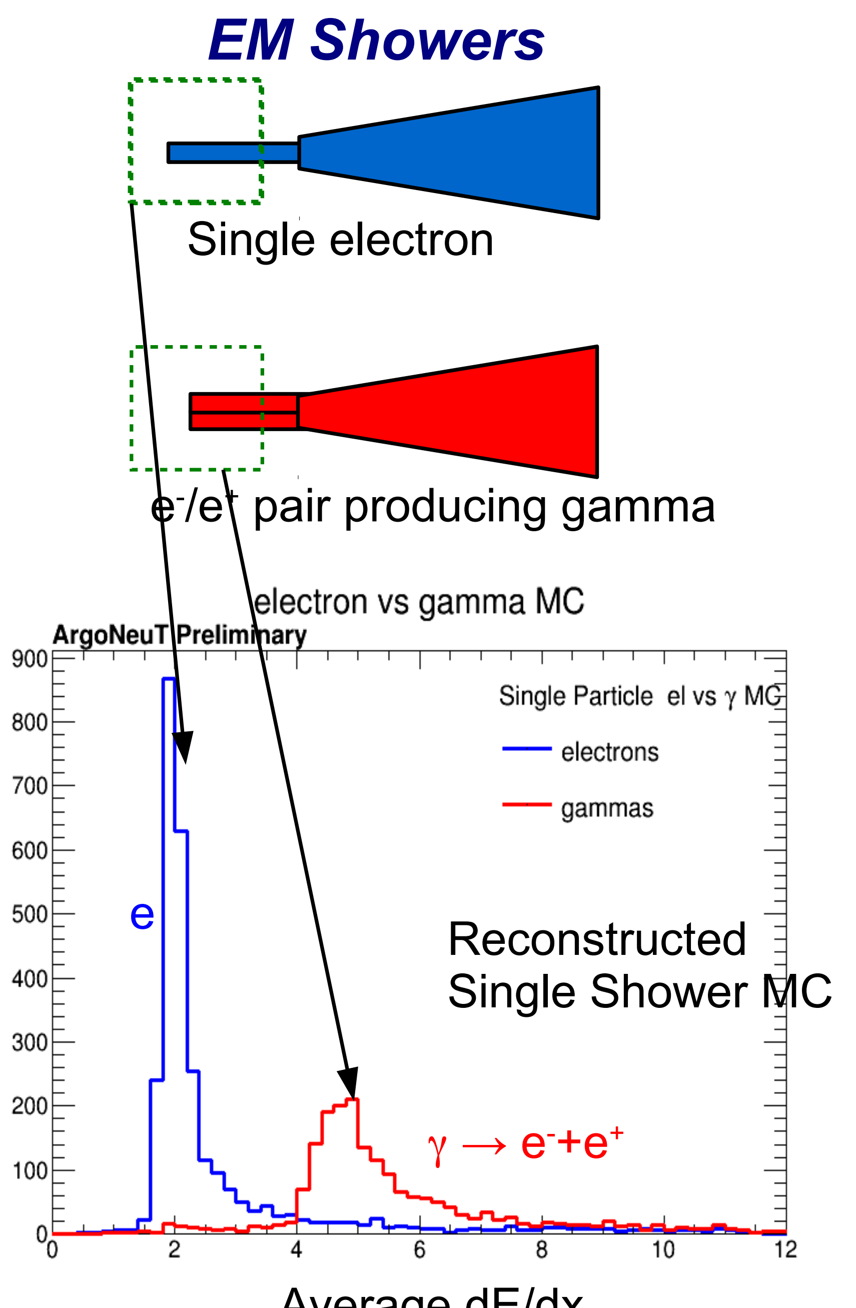
Distinguishing electrons vs. photons relies on ability to reconstruct energy at beginning of electromagnetic shower, and is significantly enhanced by capability to see displaced vertices.

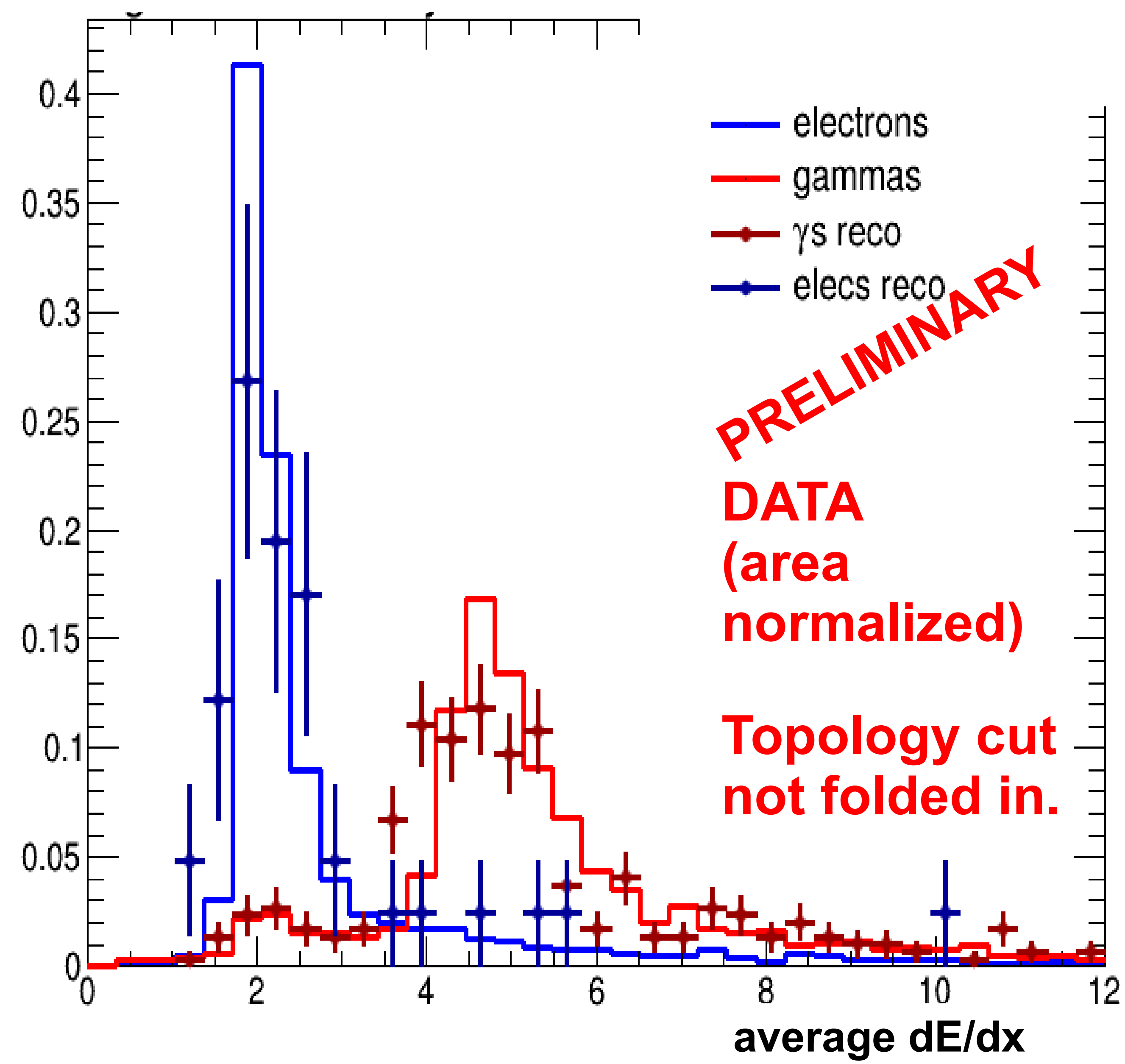




Particle Identification

- Electron/Photon distinction provided by dE/dx difference at beginning of shower, plus topological clues like gaps between primary vertex and shower start.
- Very important capability for electron-neutrino appearance analyses.
- How does choice of single/dual phase alter this?

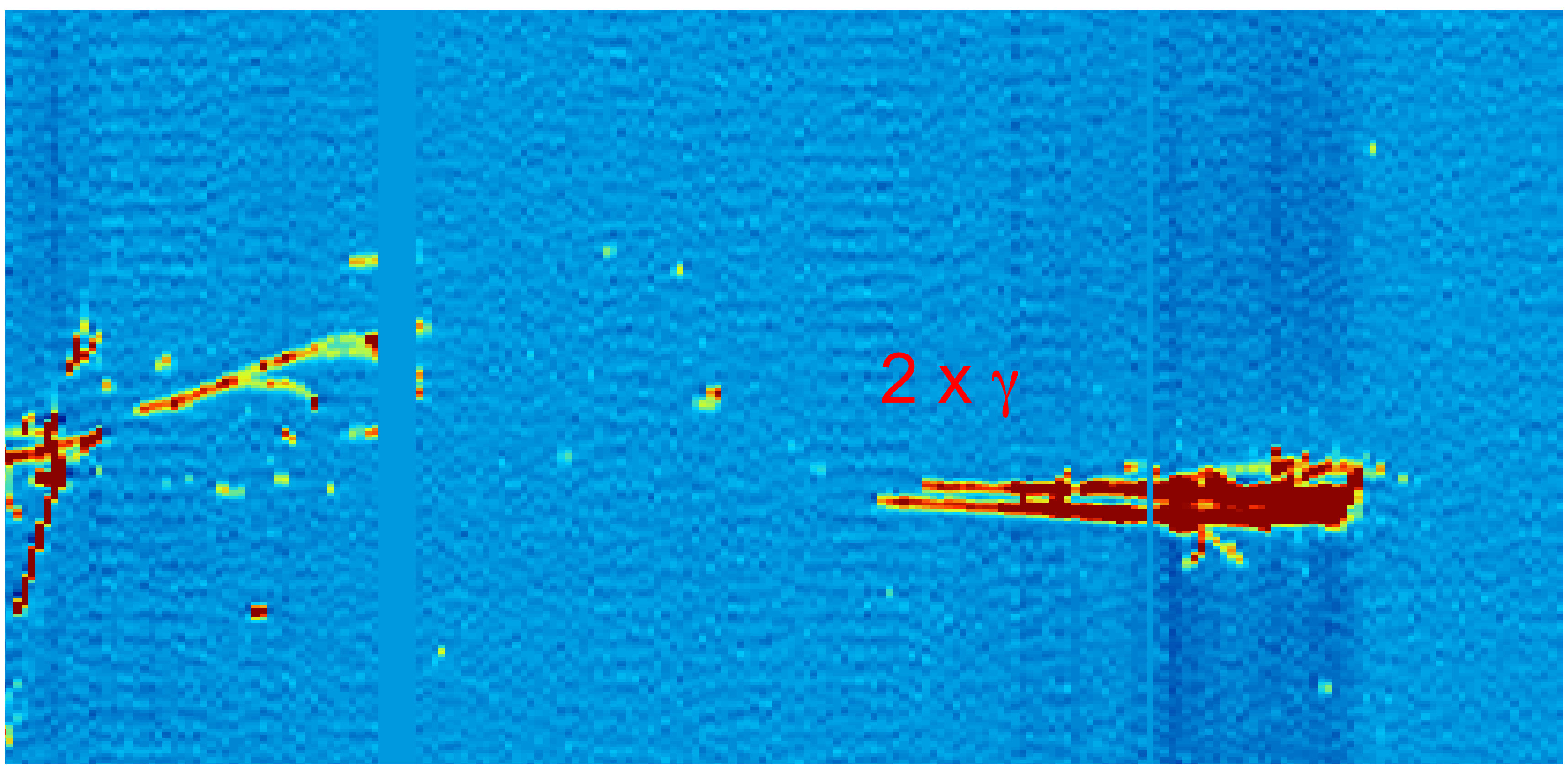




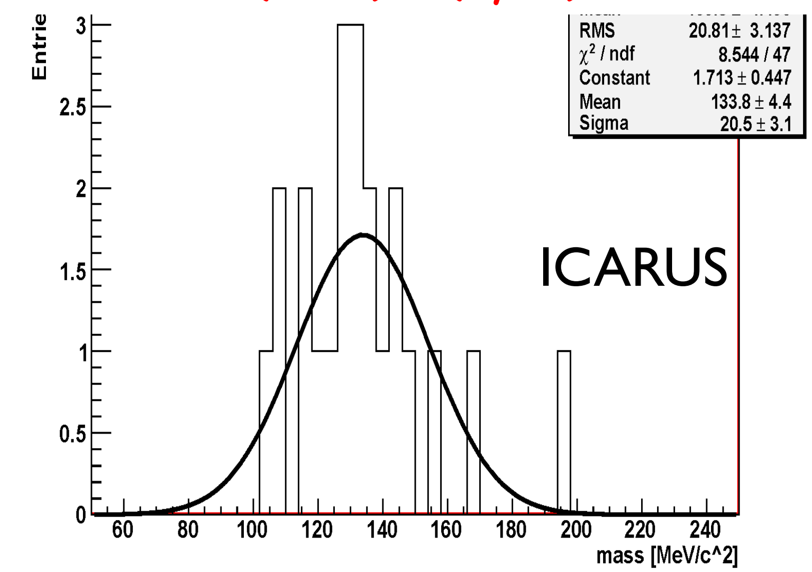
Refs:
1.)A. Szelc, Neutrino 2014

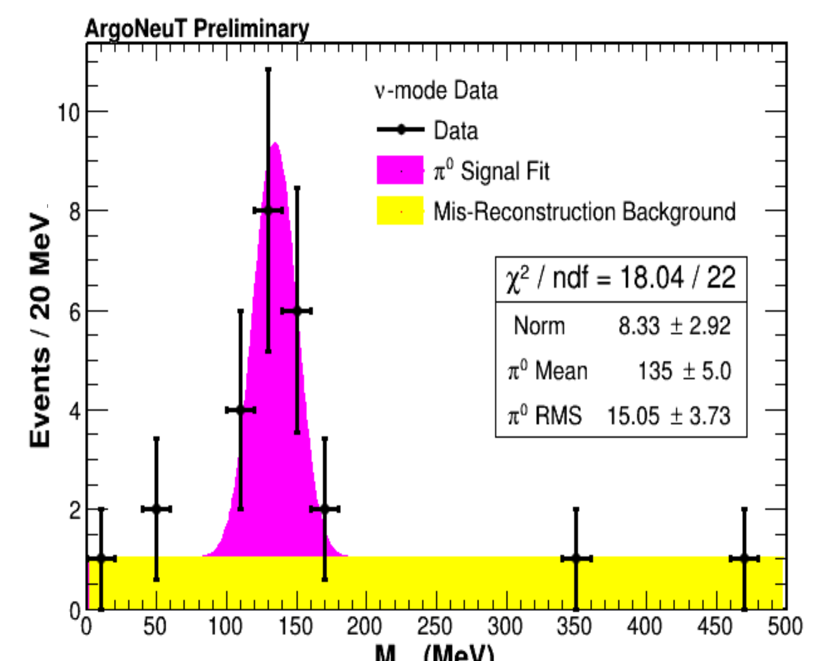
Particle Identification

- Neutral pions can be identified through both calorimetry and topology.
- Two showers, with photon-like dE/dx, pointing to a common vertex.
- A high-statistics pi0 sample would be a good sandbox for fine-tuning electromagnetic shower response.



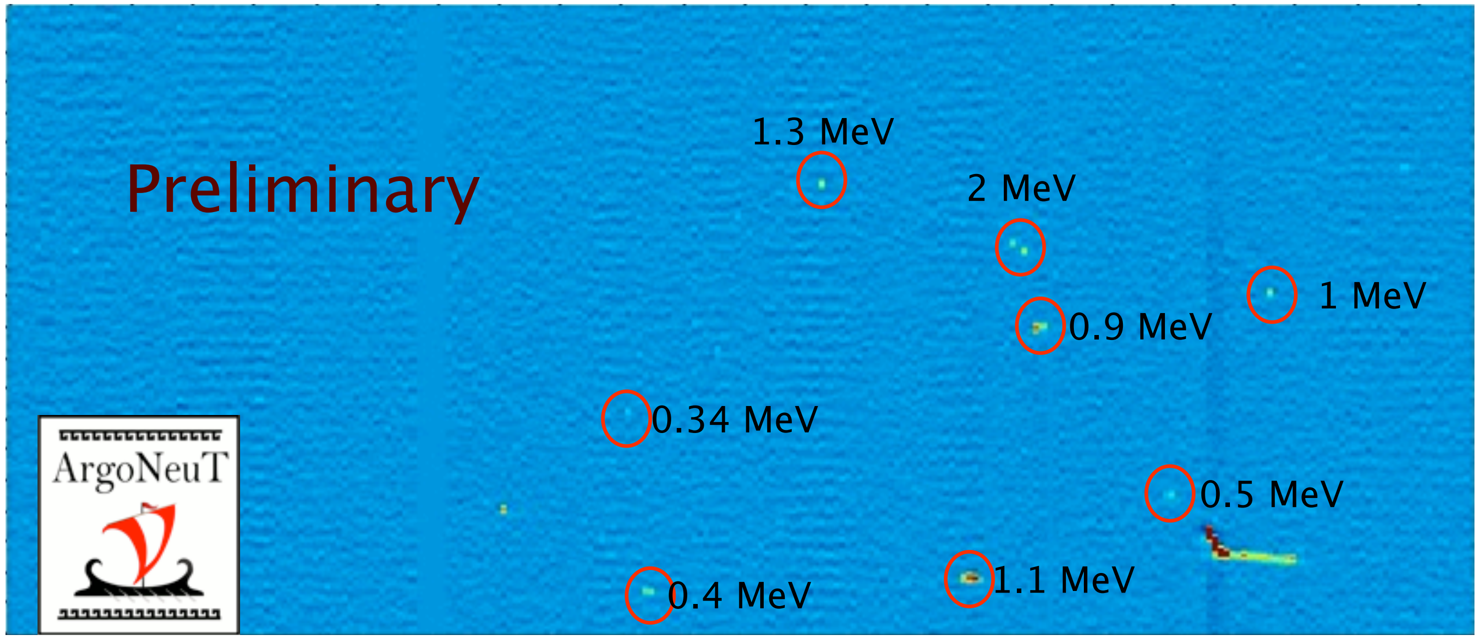
$M_{\gamma\gamma}$:
133.8±4.4(stat)±4(syst) MeV/c²

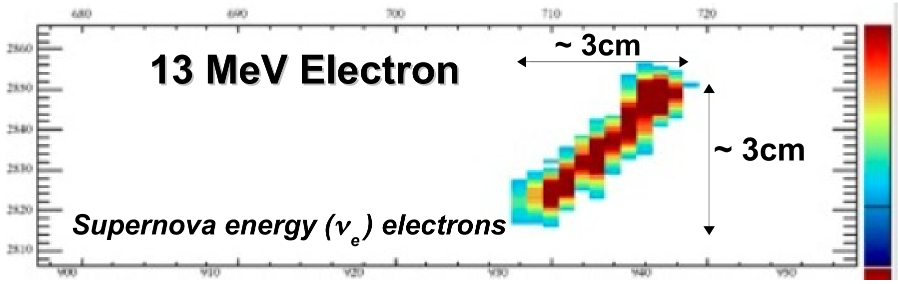




Low-energy events

- Granularity of anode planes, coupled with low-noise electronics and good electron lifetime, enables detection of very low-energy depositions.
- Very interesting physics: gamma de-excitations, radioactive decays, neutron recoils, supernova neutrinos
- Need to develop systematics/uncertainties for measuring these low-energy depositions.
- Folding in data from photon-collection system (one with good coverage) will be important here.





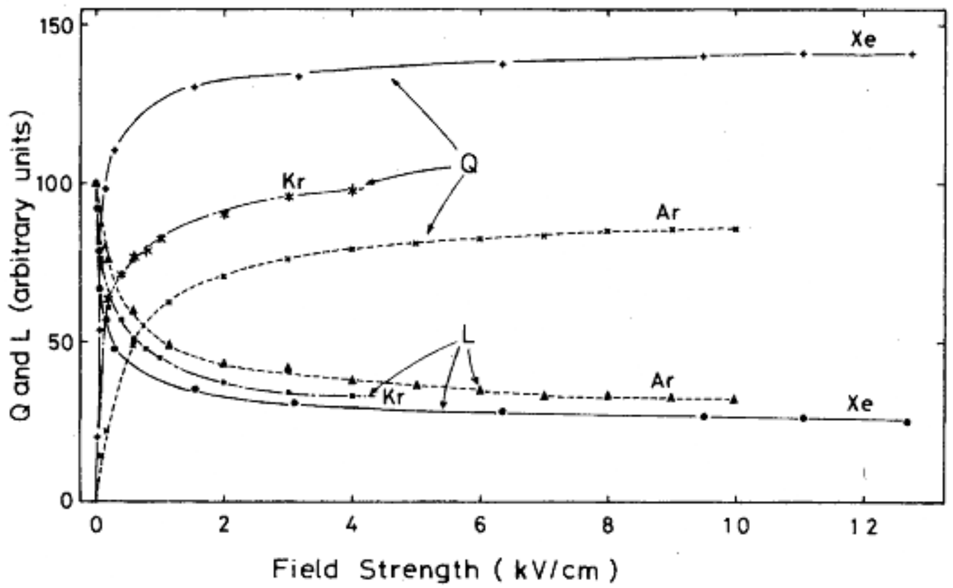


FIG. 2. Variation of relative luminescence intensity L and collected charge Q in liquid argon, krypton, and xenon vs applied-electric-field strength for 0.976- and 1.05-MeV electrons.

Refs:
1.) *Dynamical behavior of free electrons in the recombination process in liquid argon, krypton, and xenon* , S.Kubota, M.Hishida, M.Suzuki, J.Ruan(Gen), Phys. Rev. B20 (1979), 3486

Particle Identification

- Muon momentum can be measured by investigating multiple-scattering.
- This will be a vital tool for experiments like MicroBooNE and LAr1-ND, which will have a sizable fraction of events with non-contained muons.
- ICARUS has developed this technique and applied it to sample of stopping muons (allows comparisons of calorimetric and MS momenta).

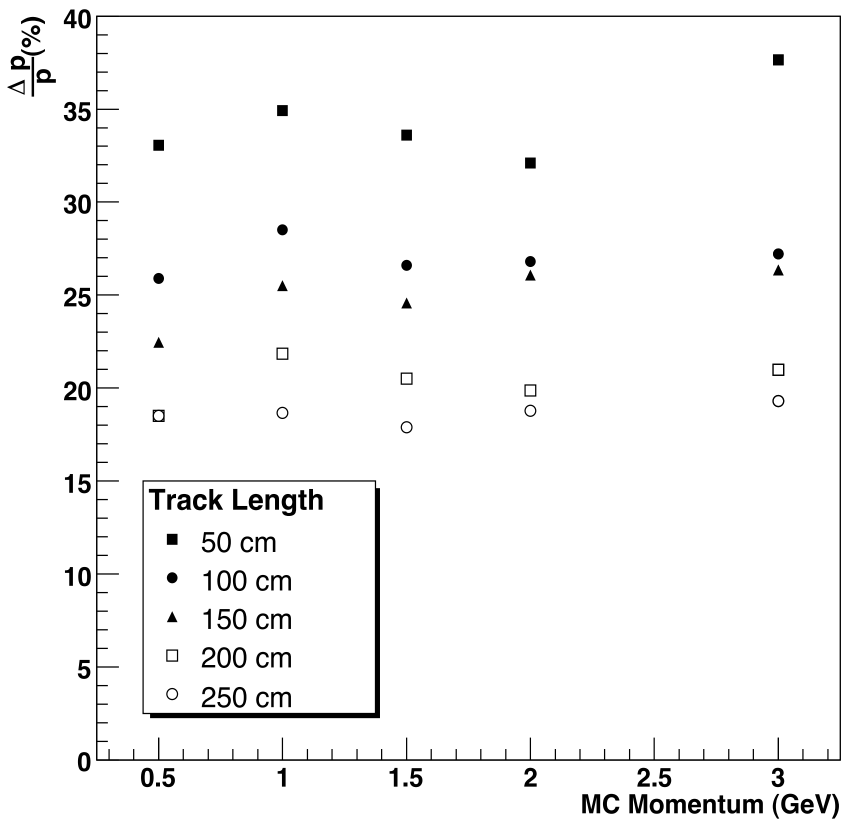
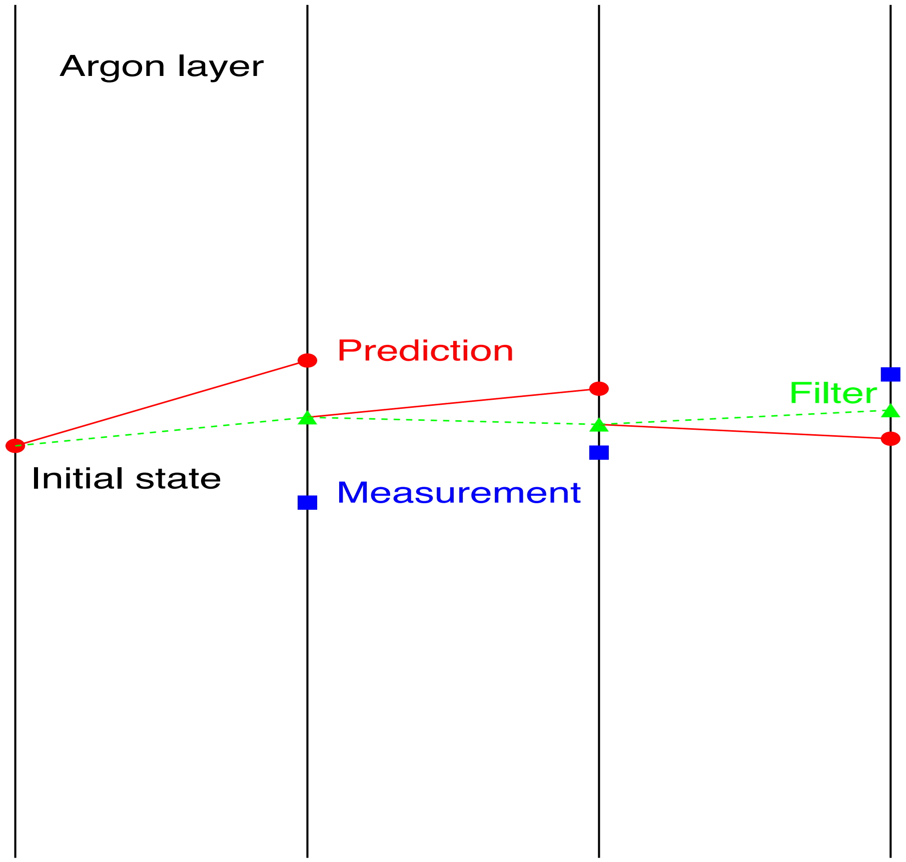


Fig. 8. Kalman Filter algorithm: Monte-Carlo momentum resolution as a function of the recorded track length.

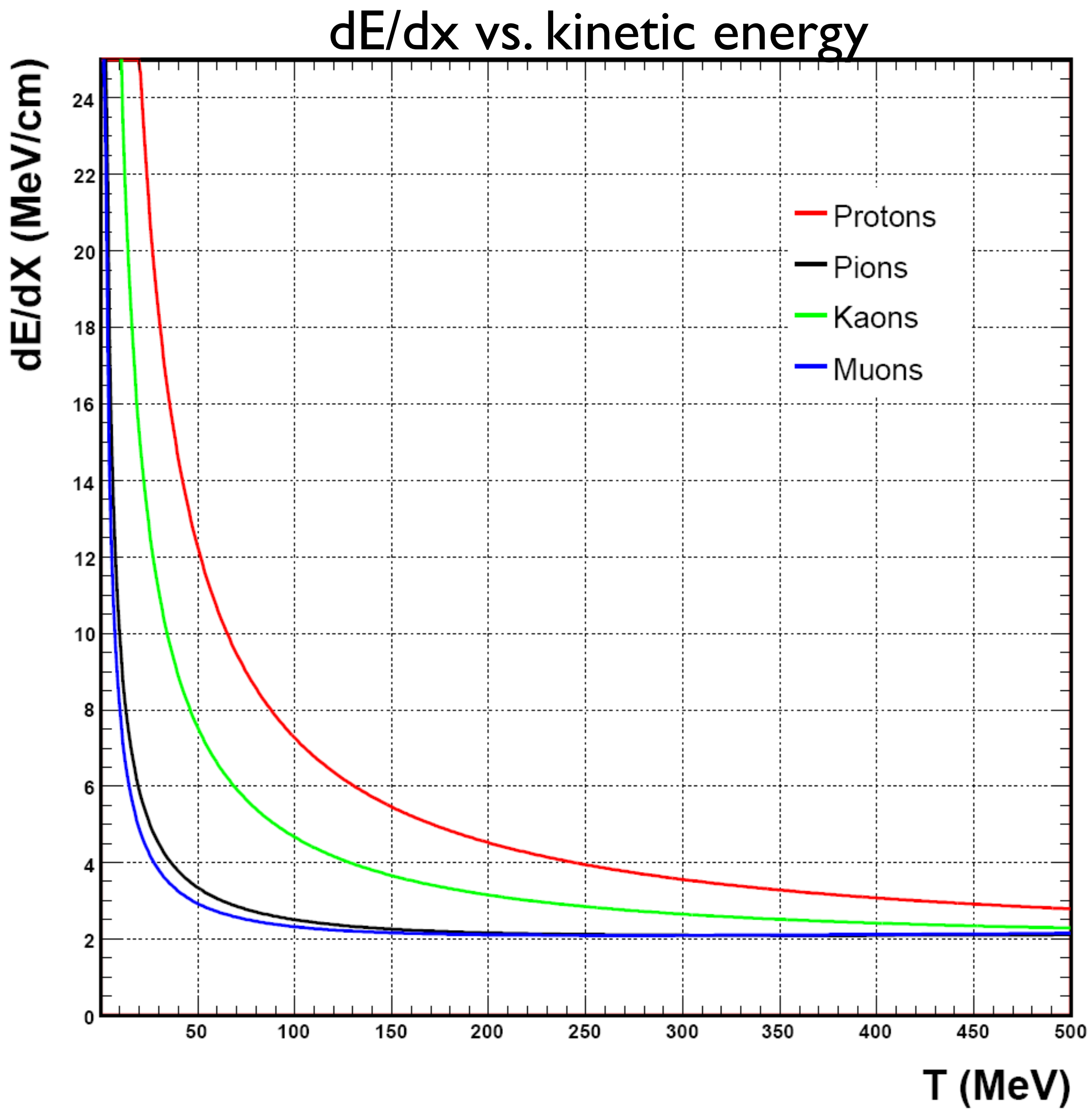


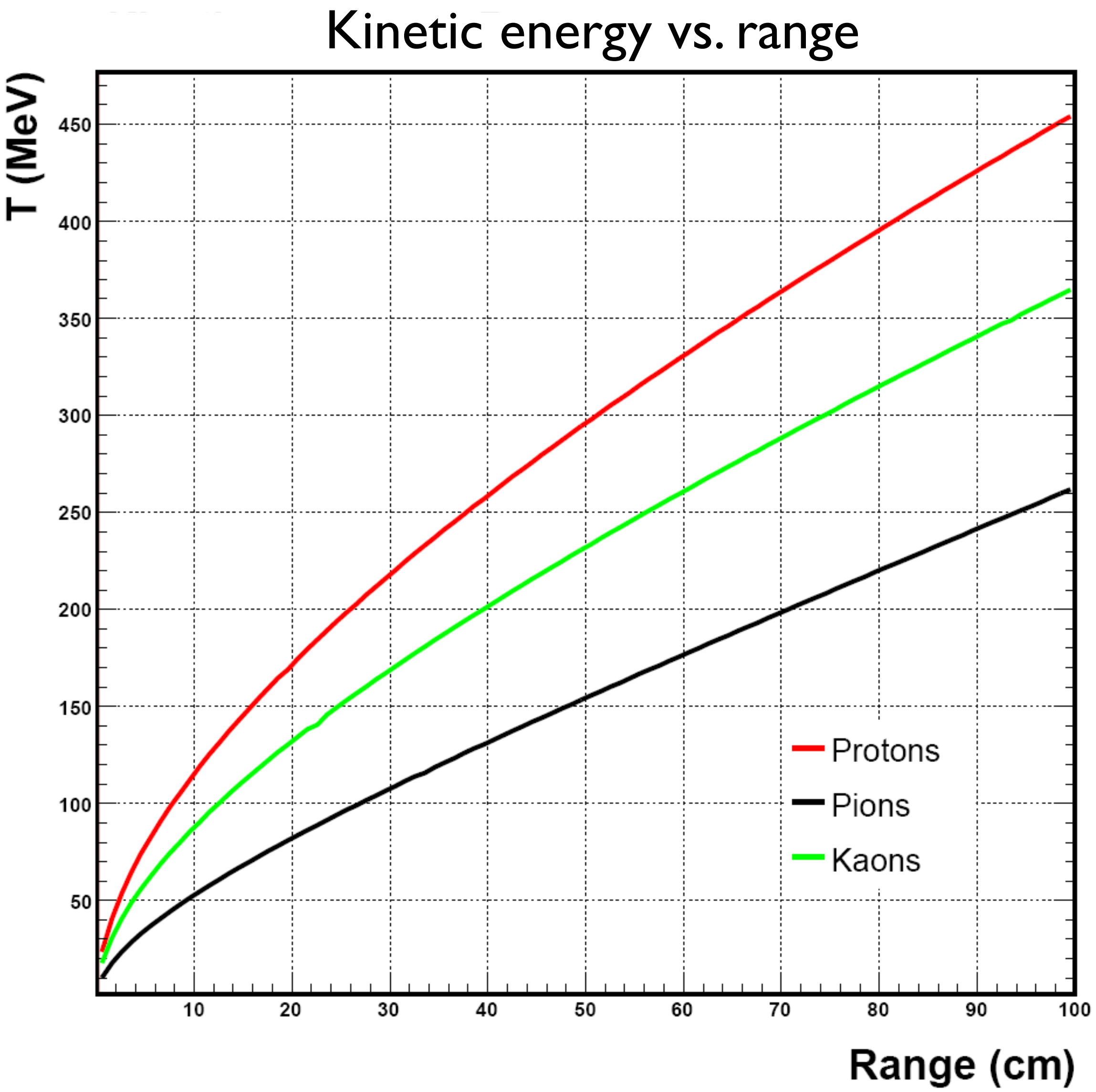
Refs:

1.)*Measurement of Through-Going Particle Momentum By Means of Multiple Scattering With The ICARUS T600 TPC*, A. Ankowski et al, hep-ex/0606006

Particle Identification

- Particles in the detector have distinct energy-deposition profiles as they come to a stop.
- A likelihood comparison is performed between the energy-deposition profile of a reconstructed track and predictions from GEANT
- Notice that this technique offers little power to distinguish muons from pions.

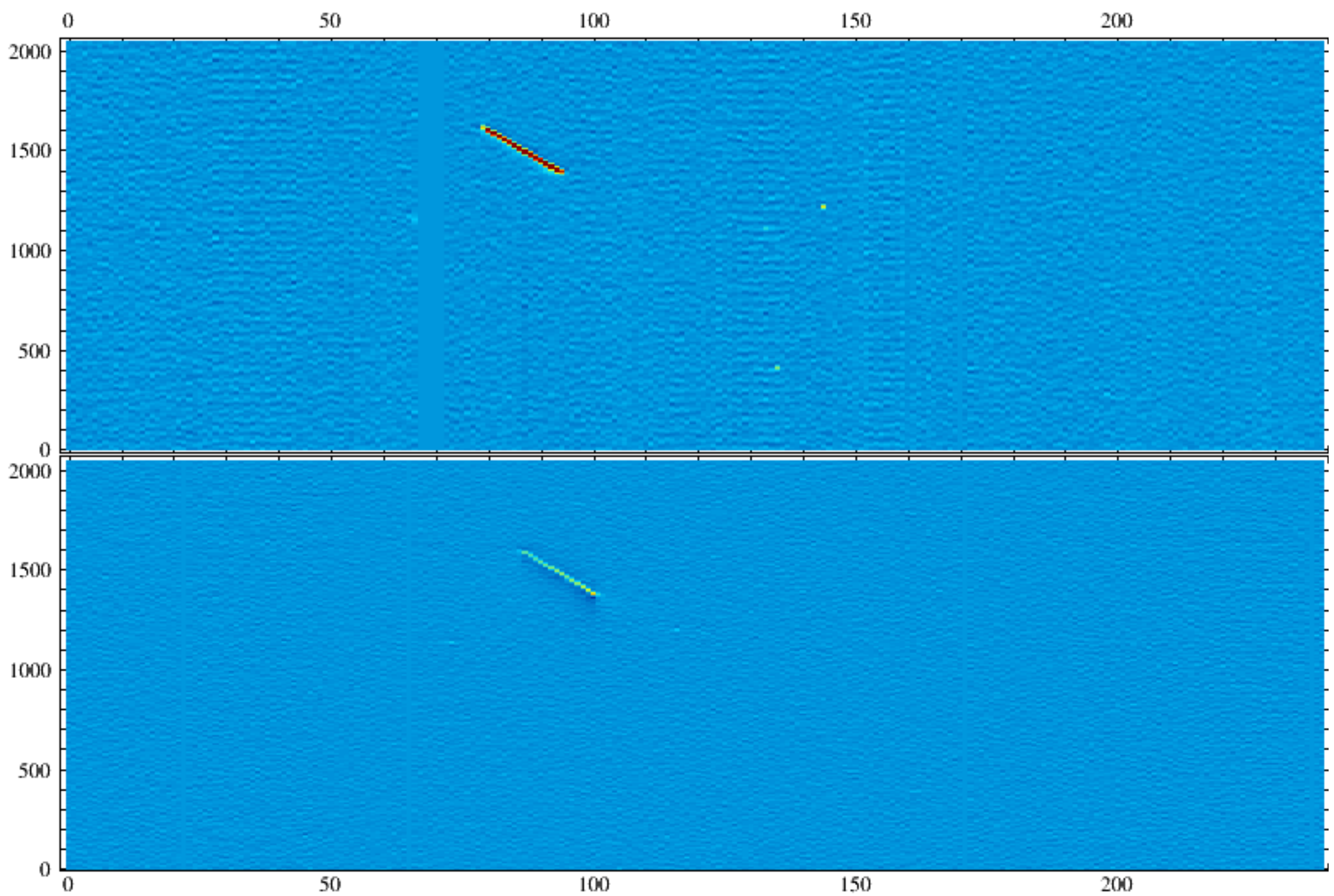


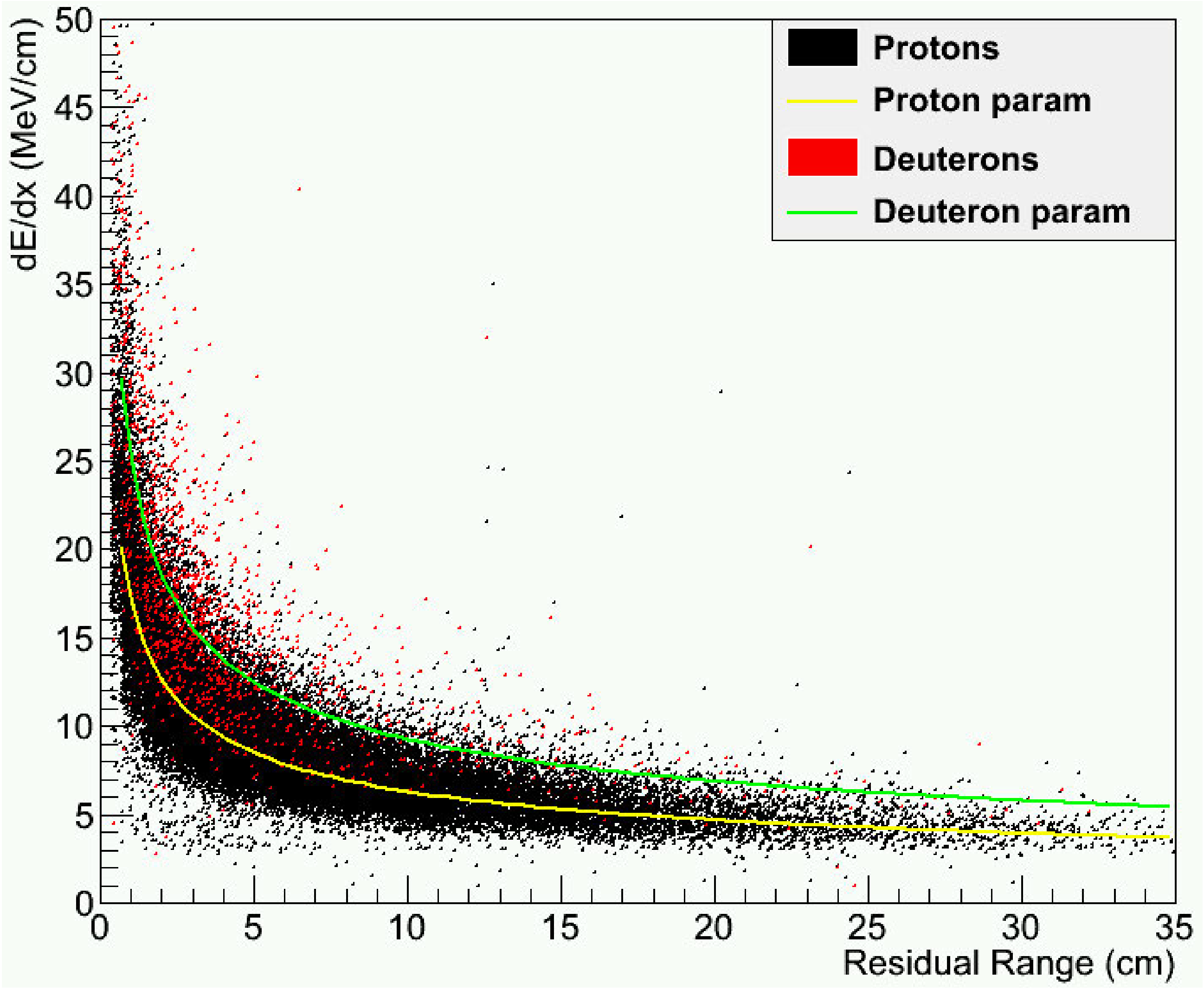


Particle Identification

- ArgoNeuT has used this dE/dx vs. range technique in a variety of analyses, such as a study of a sample of isolated, highly-ionizing tracks.

- We currently use data from GEANT/NIST. Would like to have data-based versions of these particle parameterizations.



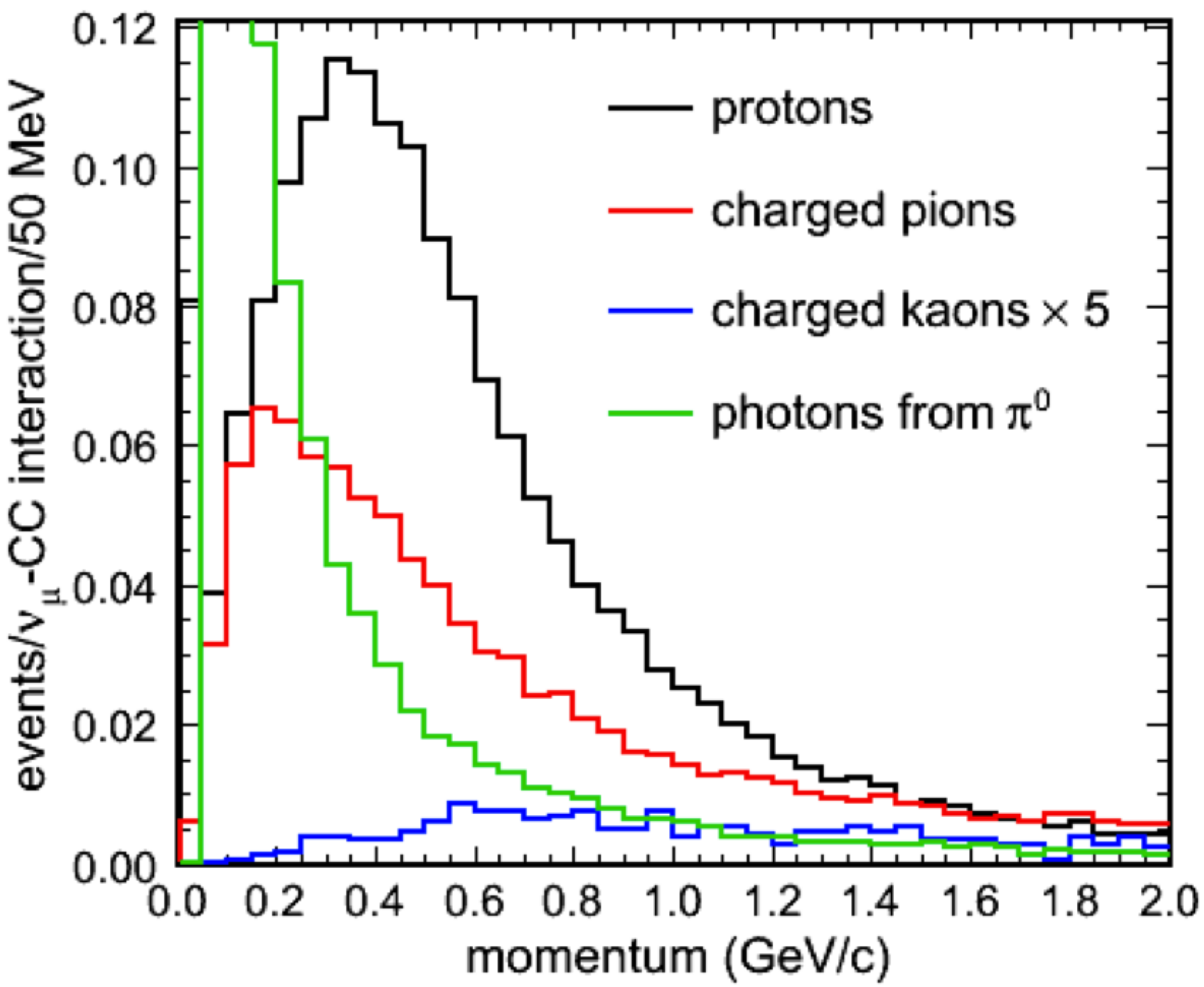


Refs:
1.) *A study of electron recombination using highly ionizing particles in the ArgoNeuT Liquid Argon TPC*, R. Acciarri et al, 2013 JINST Vol. 8 P08005

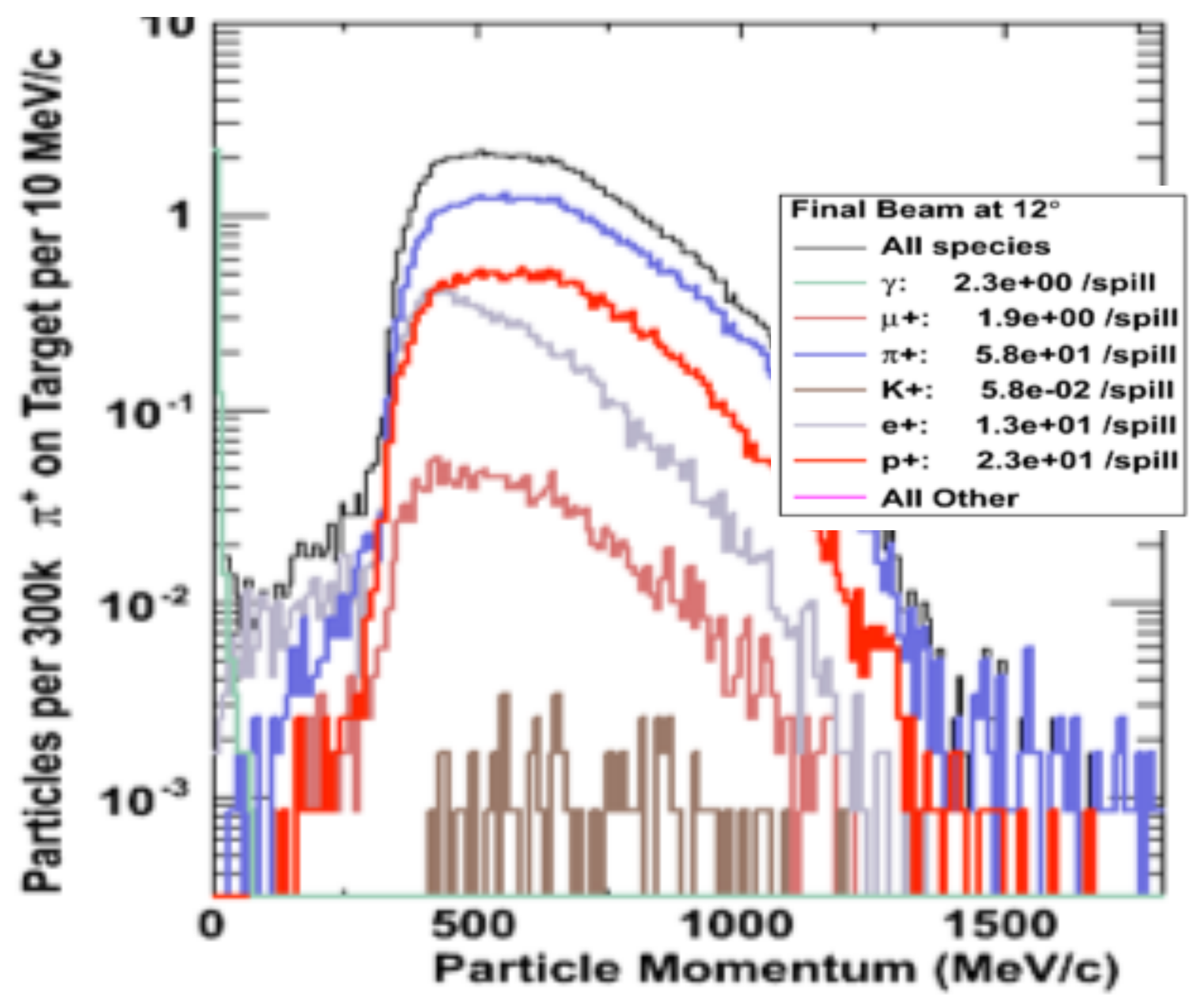
Calibration: LArIAT

- LArIAT collaboration is about to operate a small LArTPC in the Fermilab test-beam facility.
- Beam profile is well matched to expected beam energies of future experiments, such as ELBNF.

NuMI LE On-axis Beam



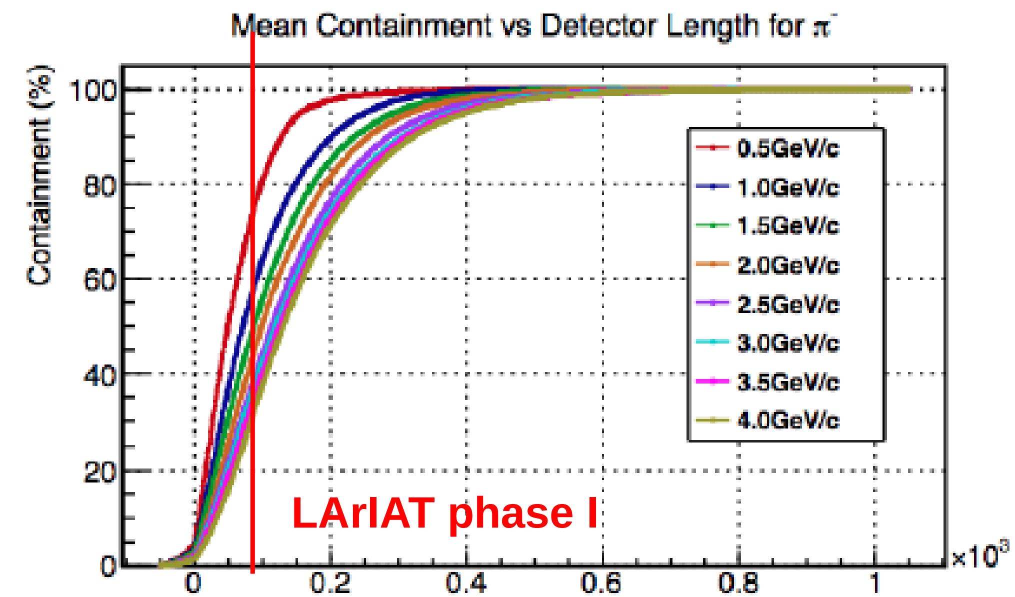
LArIAT Beam

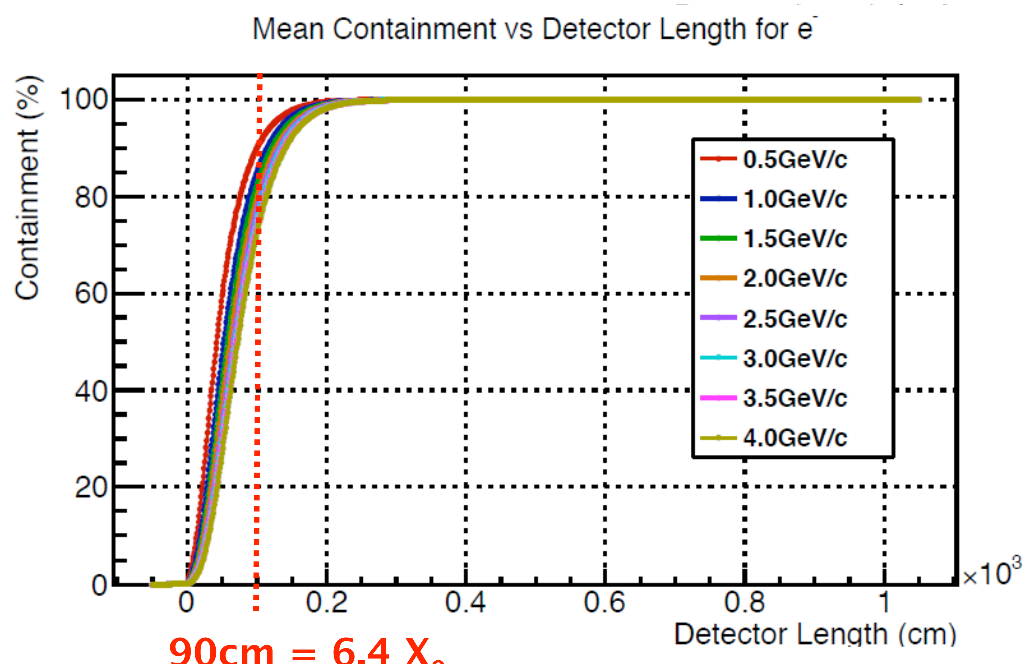


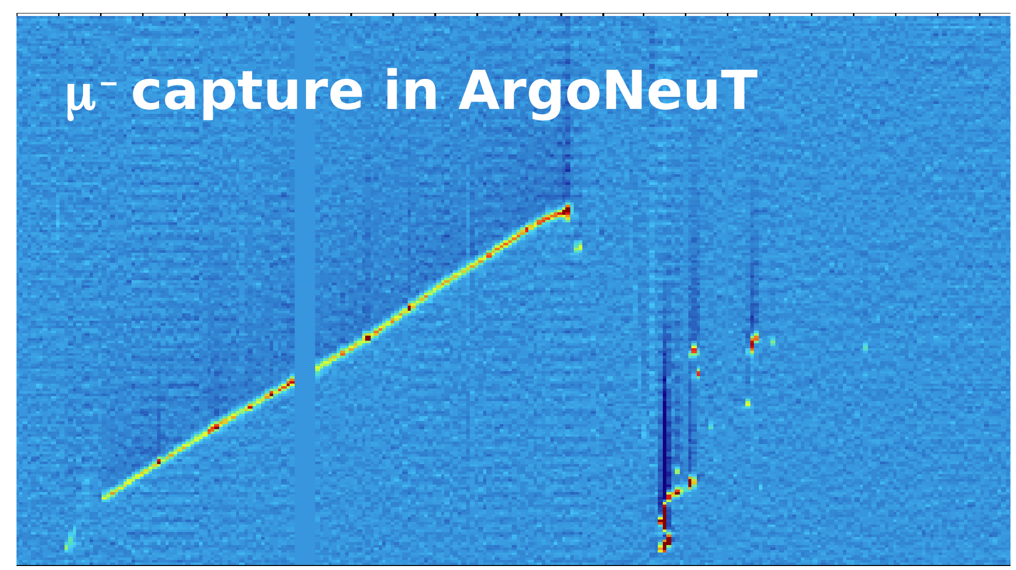
Refs:
1.)*LArIAT: Liquid Argon In A Testbeam*, J. Paley et al, hep-ex/1406.5560

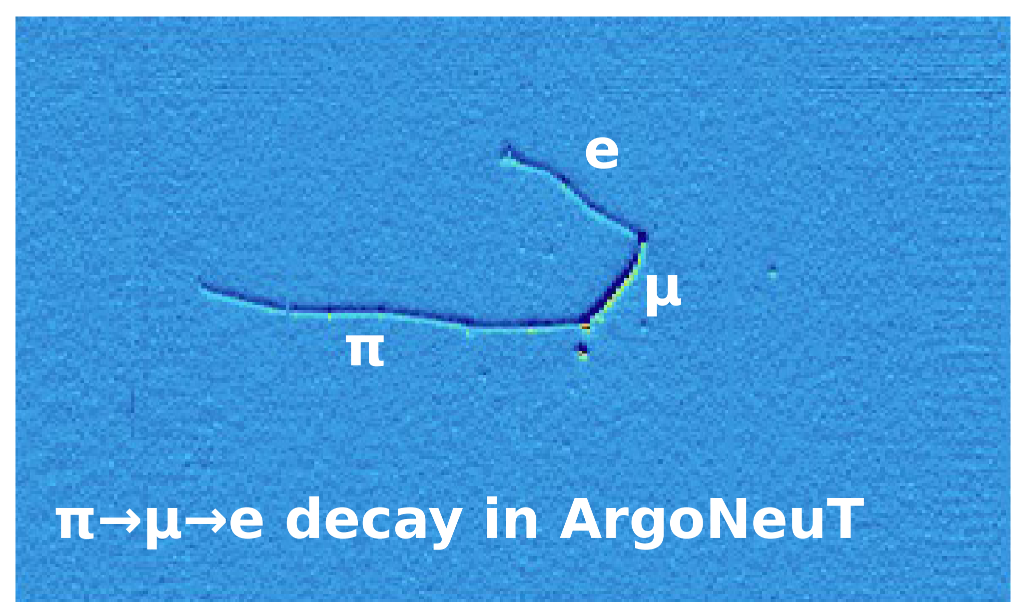
Calibration: LArIAT

- Test-beam exposure, LArIAT, will give us an invaluable data sample to measure dE/dx profiles for stopping particles of known identity (among other topics).
- Can also study dependance of recombination on electric-field.
- Beam polarity is tunable, so can study possibility of muon sign-selection in non-magnetized detector (using 100% mu+ decay, and ~75%/25% mu- capture/decay).



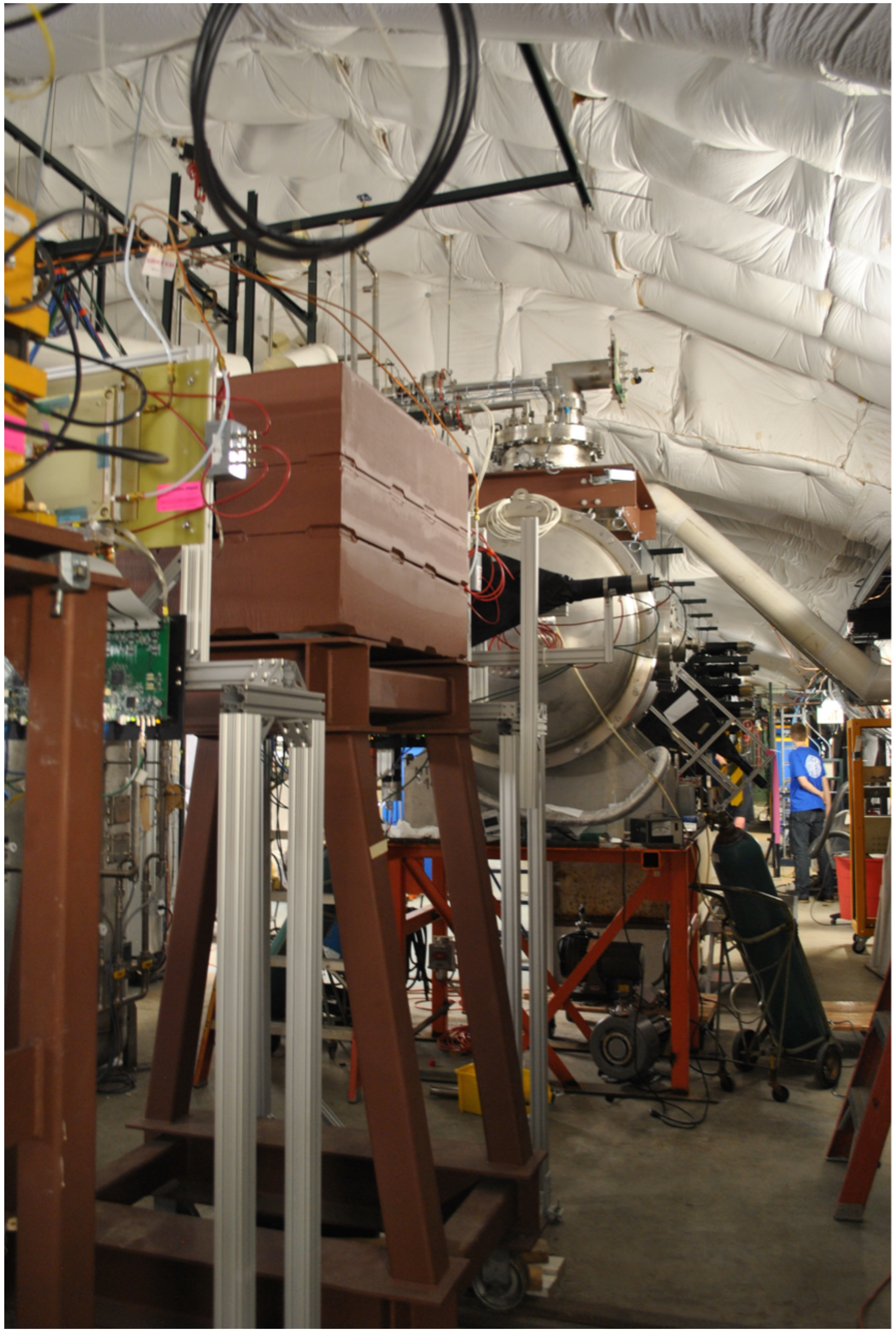




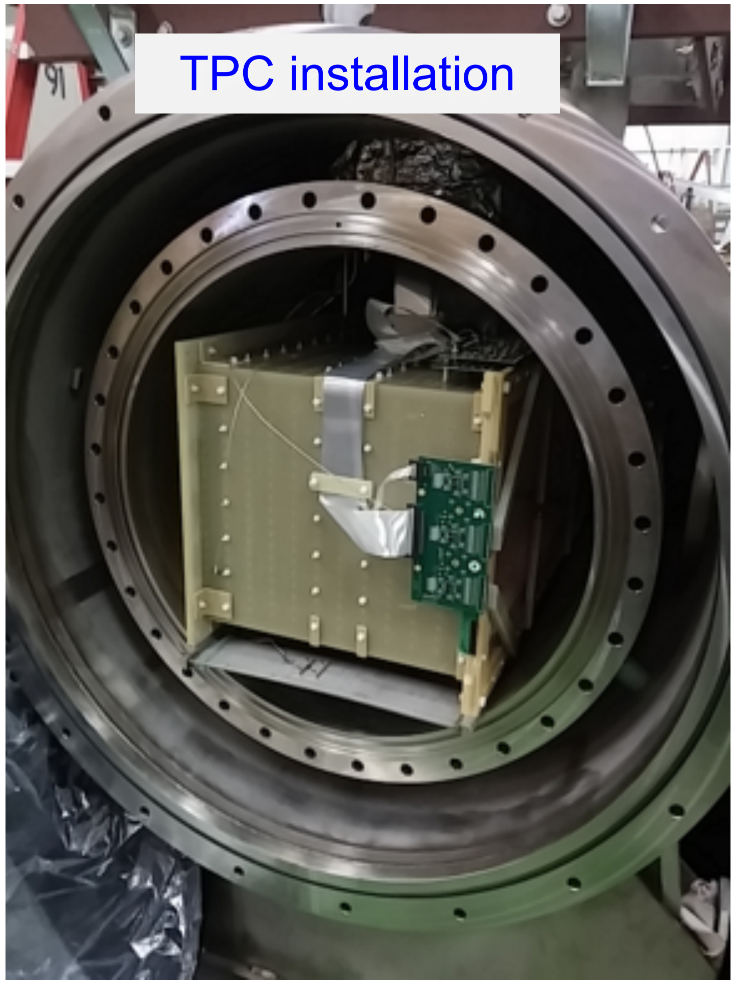


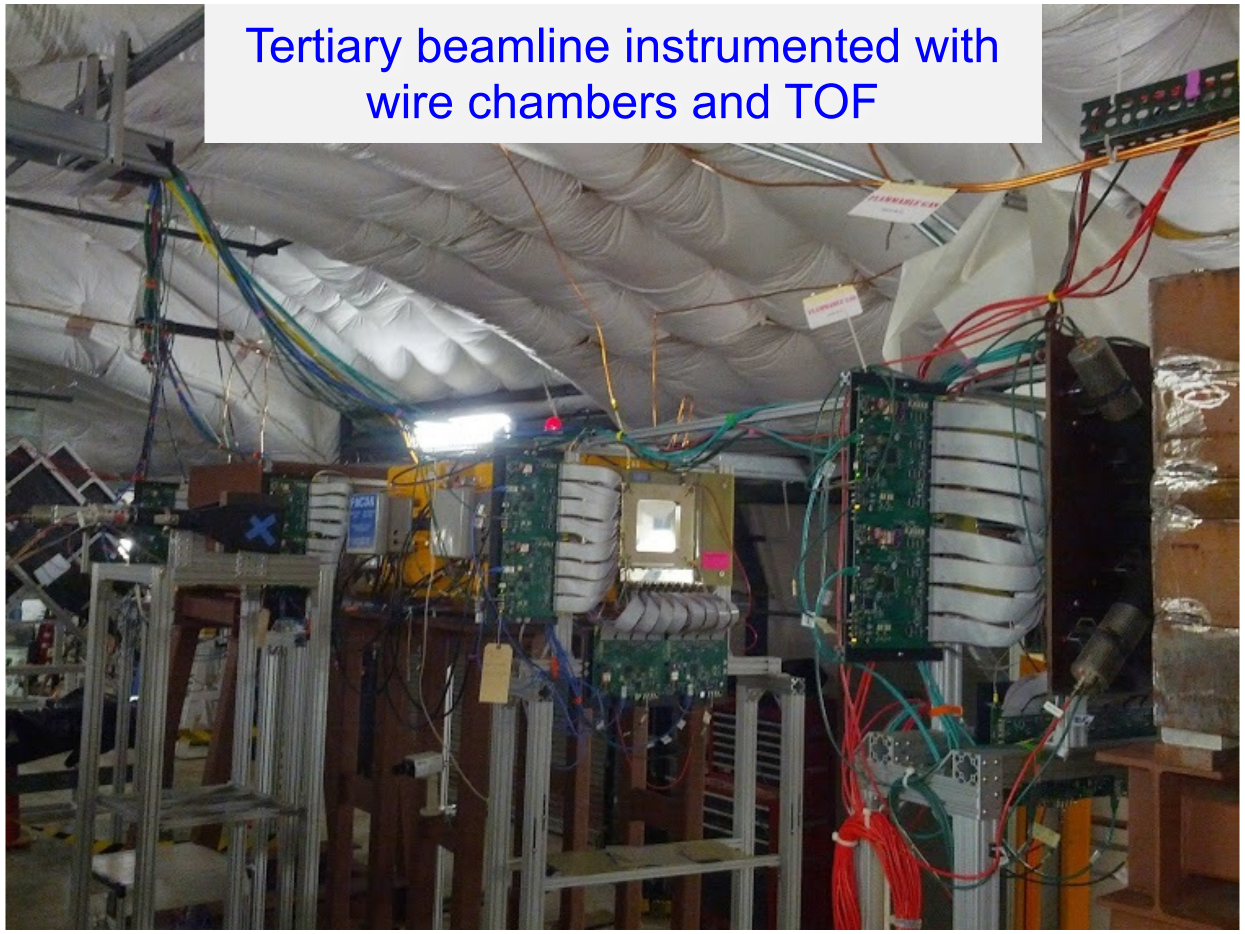
Calibration: LArIAT

- LArIAT detector subsystems are installed in test-beam facility at Fermilab, and start of operations is expected this spring.
- This will provide a wealth of charged-paricle data that we will use to benchmark LArTPC performance.
- Can do systematic studies of detector performance as a function of: drift-field, particle momenta, particle species, etc…

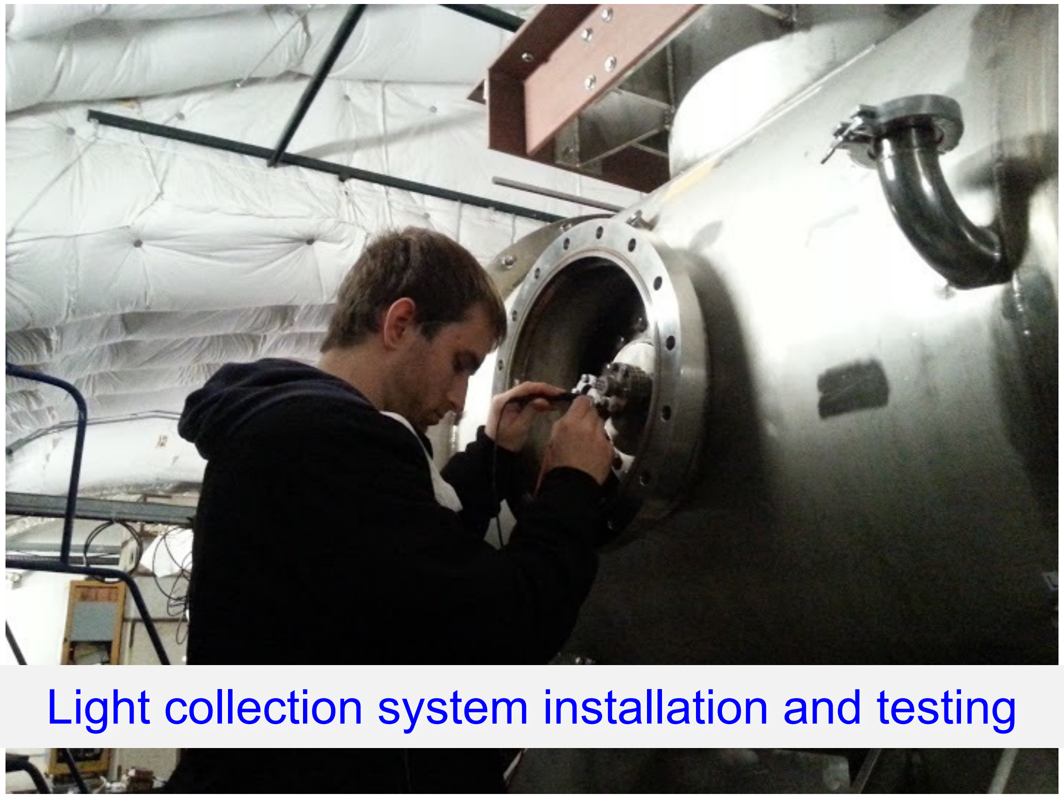


Calibration: LArIAT


TPC installation

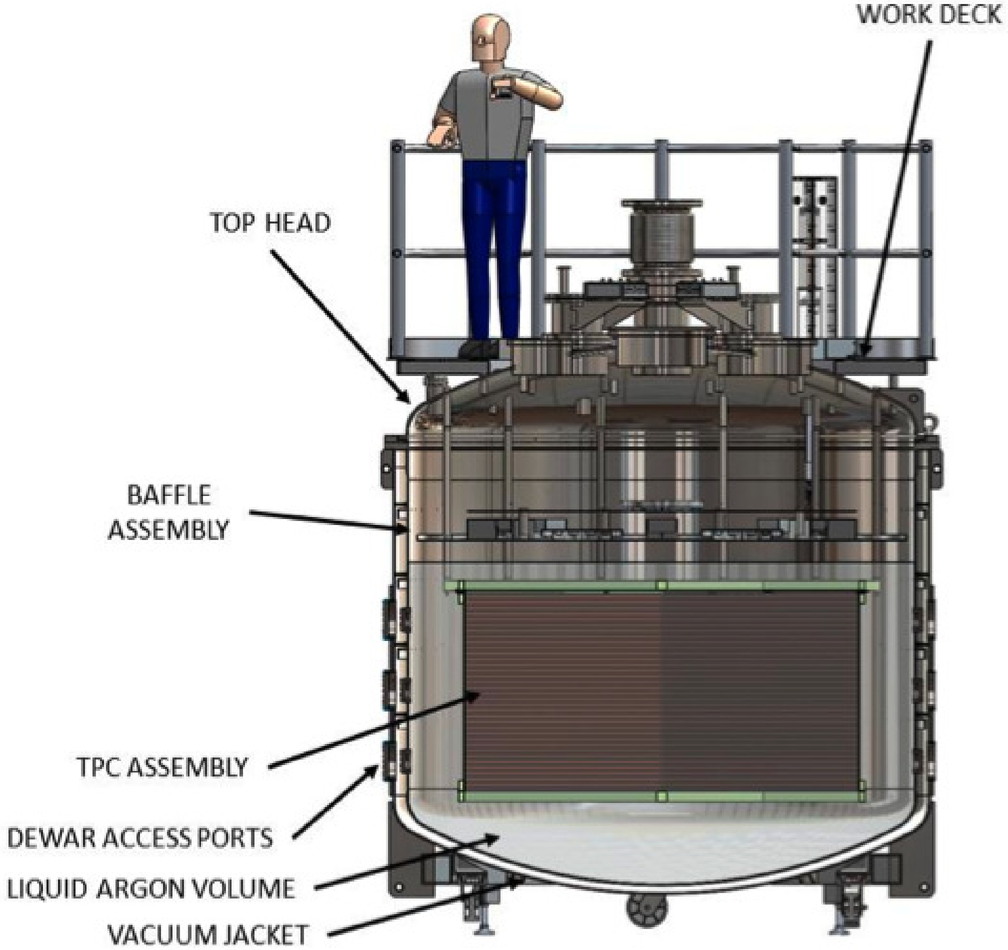

Tertiary beamline instrumented with wire chambers and TOF

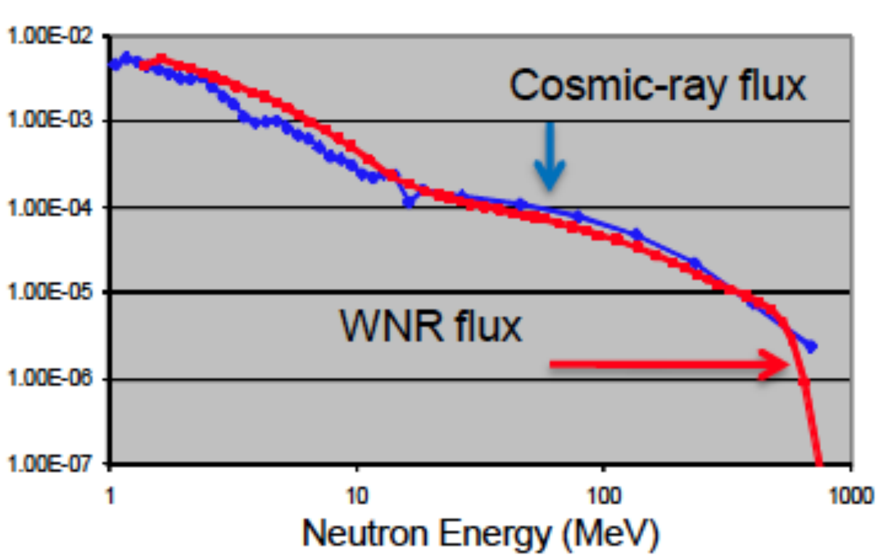

TPC wire plane installation and testing


Light collection system installation and testing

Calibration: CAPTAIN

- The CAPTAIN detector has been built to study the response of LArTPCs to neutrons.
- Surface detectors (MicroBooNE/LAr1ND) will collect neutrons from cosmic-ray-induced sources, and surface/underground detectors will see neutrons induced by neutrino interactions in surrounding material.
- The high-statistics sample of neutrons collected by CAPTAIN will be invaluable for understanding low-energy event reconstruction (relevant for supernova physics), and for providing input to help identify neutrons in neutrino interactions.





Refs:
1.)*The CAPTAIN Detector and Physics Program*, H. Berns et al, hep-ex/1309.1740

Conclusions

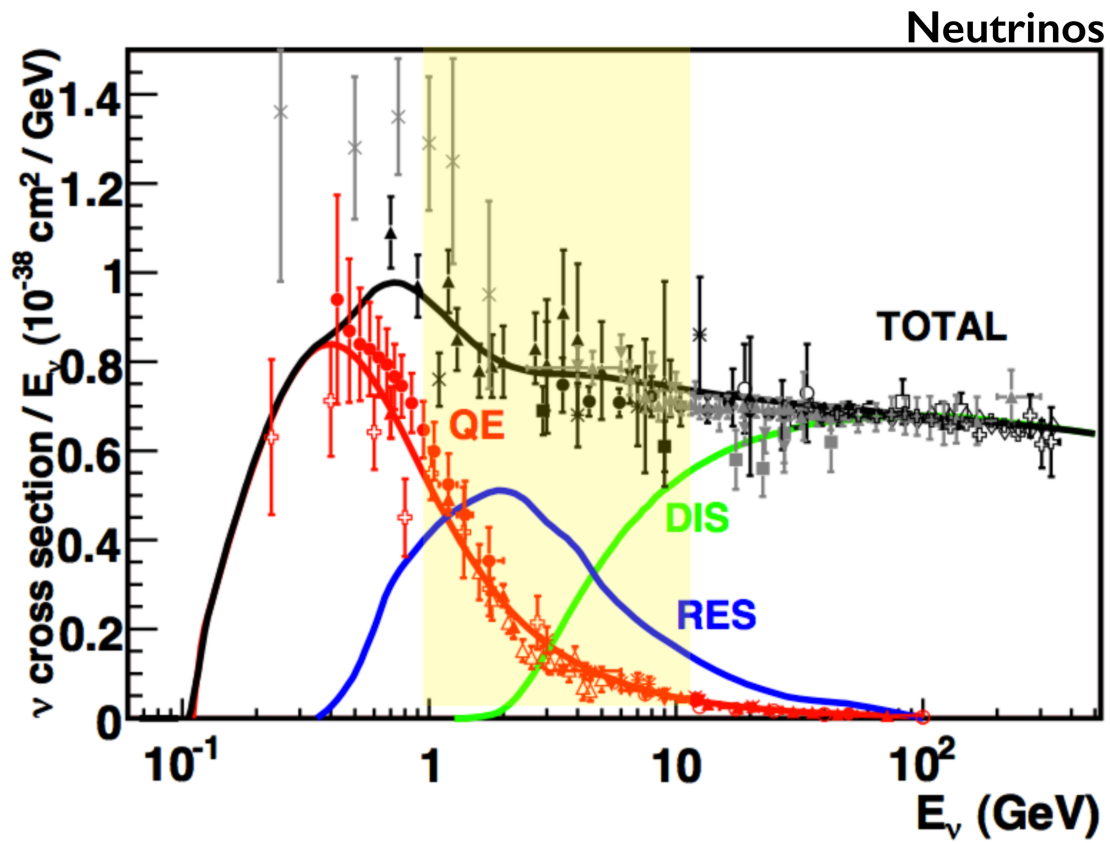
- We have learned a great deal about LArTPC capabilities from existing efforts (ArgoNeuT, ICARUS,…). We are just scratching the surface.
- With MicroBooNE/LArIAT/CAPTAIN about to start up we are poised to learn much more. A flood of new data is coming SOON…big challenge to be ready for it.
- Robust understanding of capabilities of LArTPCs is essential for neutrino experiments (MicroBooNE, CAPTAIN-BNB/MINERVA, SBN, ELBNF) to achieve, and exceed, desired physics goals.
- Apologies to any experiments/analyses that I neglected.

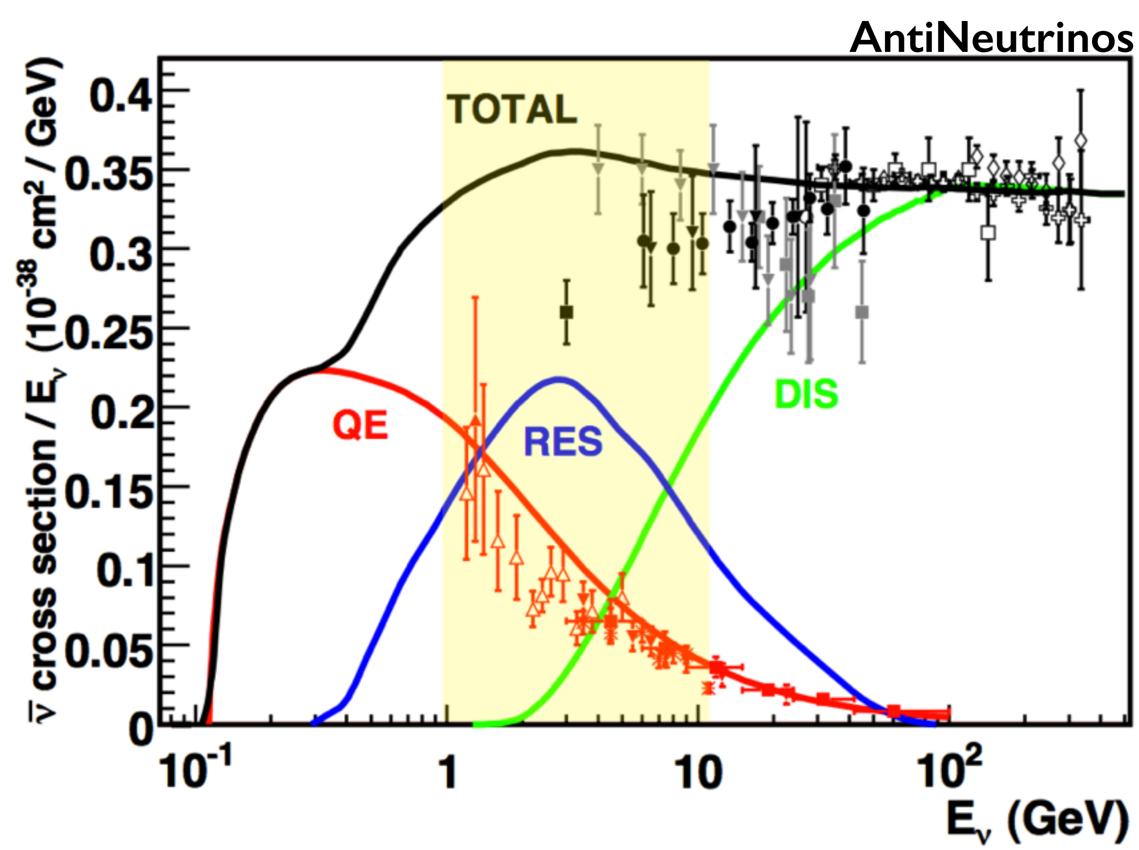
Back-Up Slides

Neutrino Interactions

- Neutrino experiments that will search for CP-violation are operating in an energy-regime where several competing processes are active.

- Nuclear targets in these experiments (*e.g.* - Carbon, Argon, Oxygen, etc…) introduce complications that can skew picture of observed interactions.



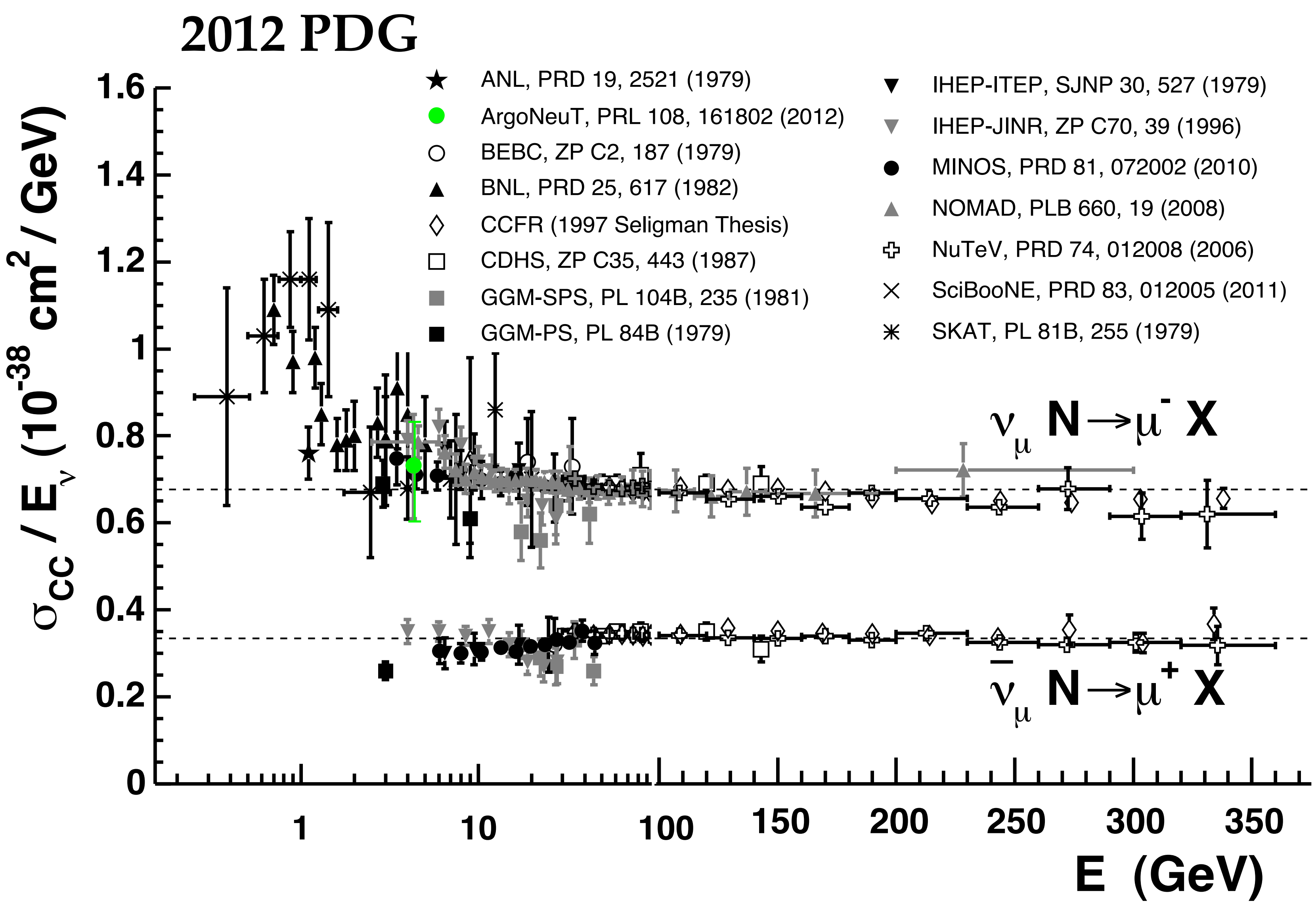


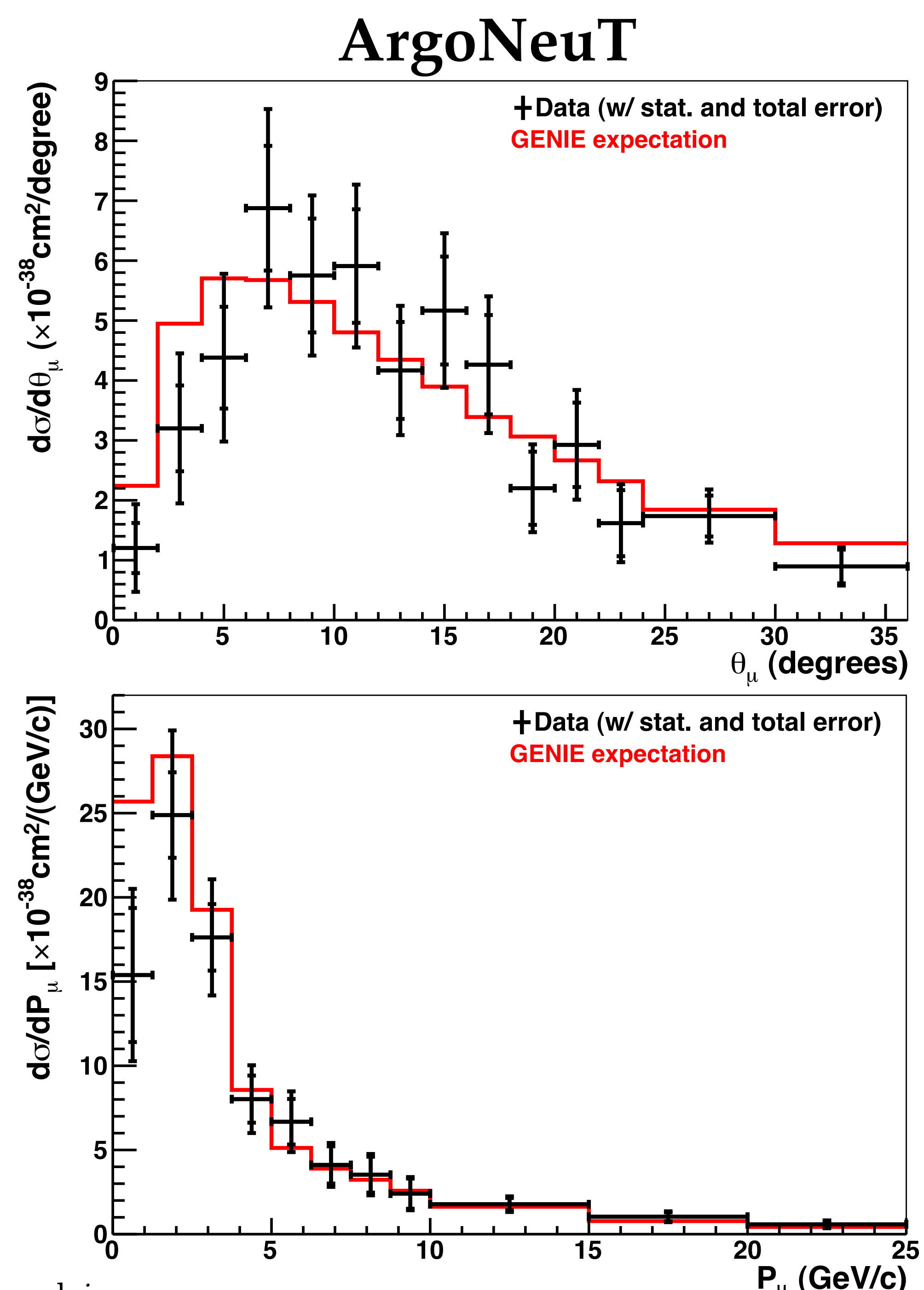
Why Noble Liquids for Neutrinos?

- Abundant ionization electrons and scintillation light can both be used for detection.
- If liquids are highly purified (<0.1ppb), ionization can be drifted over long distances.
- Excellent dielectric properties accommodate very large voltages.
- Noble liquids are dense, so they make a good target for neutrinos.
- Argon is relatively cheap and easy to obtain (1% of atmosphere).
- Drawbacks?...no free protons...nuclear effects.

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165	373
Density [g/cm	0.125	1.2	1.4	2.4	3	1
Radiation Length [cm]	755.2	24	14	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

ArgoNeuT: Physics





Inclusive CC cross-section

- First Results: Using **2 weeks** of neutrino-mode data (8.5×10^{18} POT), the differential cross-section for inclusive charged-current muon neutrino production was measured.
- Analysis Selection:
  - Track originating within ArgoNeuT fiducial region.
  - Match to corresponding track in MINOS near detector.
  - MINOS track is negatively charged.

$$\frac{\partial\sigma(u_i)}{\partial u} = \frac{N_{\text{measured},i} - N_{\text{background},i}}{\Delta u_i \ \epsilon_i \ N_{\text{targ}} \ \Phi}$$

Refs:

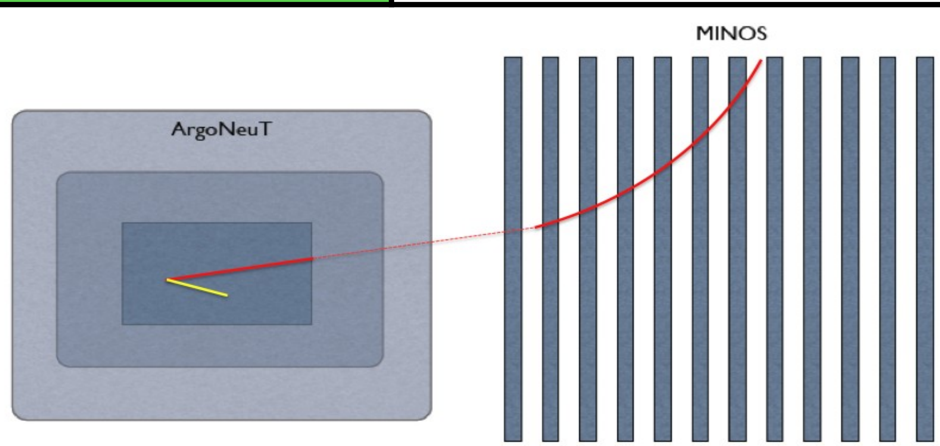
1.) *First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon*, C. Anderson et al., PRL 108 (2012) 161802, arXiv:1111.0103

2.) *Neutrino cross section measurements*, J. Beringer et al. (Particle Data Group), Phys. Rev. D**86**, 010001 (2012)

ArgoNeuT

- LArTPC operated in Fermilab's NuMI neutrino beam.
- Located upstream of MINOS near detector, which provides muon reconstruction and sign selection.
- Collected 1.35×10^{20} Protons on Target (POT).

Cryostat Volume	500 Liters
TPC Volume	175 Liters (90cm x 40cm x 47.5cm)
# Electronic Channels	480
Electronics Style (Temp.)	JFET (293 K)
Wire Pitch (Plane Separation)	4 mm (4 mm)
Electric Field	500 V/cm
Max. Drift Length (Time)	0.5 m (330 μs)
Wire Properties	0.15mm diameter BeCu



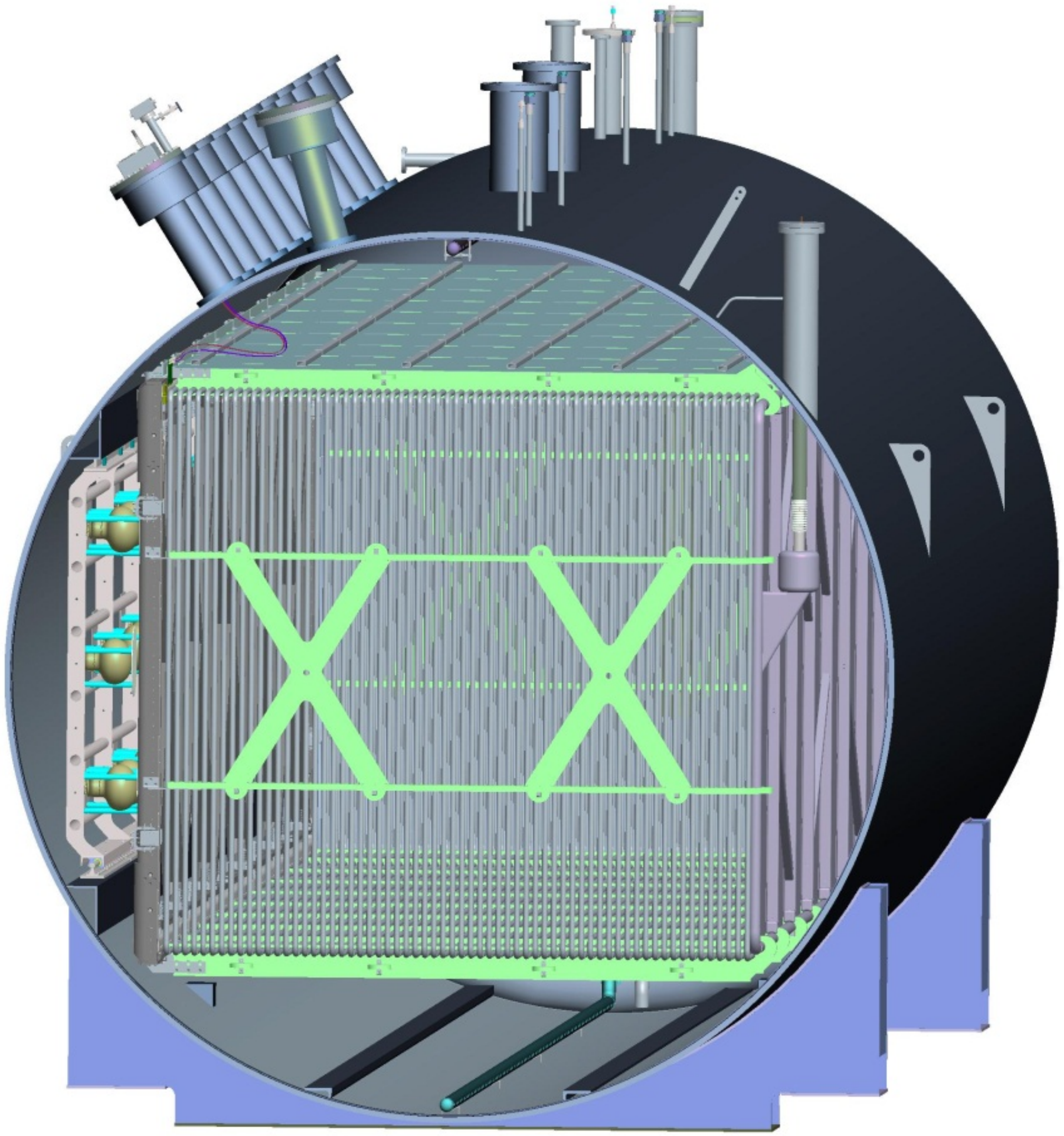
ArgoNeuT in the NuMI Tunnel

Refs:
1.) *The ArgoNeuT detector in the NuMI low-energy beam line at Fermilab*, C. Anderson et al., JINST 7 P10019, Oct. 2012, arXiv:1205.6747

The MicroBooNE Experiment

- MicroBooNE will operate in the Booster neutrino beam at Fermilab.
- Combines physics with hardware R&D necessary for the evolution of LArTPCs.
  - MiniBooNE low-energy excess
  - Low-Energy (<1 GeV) neutrino cross-sections
  - Cold Electronics (preamplifiers in liquid)
  - Long drift (2.5m)
  - Purity without evacuation.

Cryostat Volume	150 Tons
TPC Volume (l x w x h)	89 Tons (10.4m x 2.5m x 2.3m)
# Electronic Channels	8256
Electronics Style (Temp.)	CMOS (87 K)
Wire Pitch (Plane Separation)	3 mm (3mm)
Max. Drift Length (Time)	2.5m (1.5ms)
Wire Properties	0.15mm diameter SS, Cu/Au
Light Collection	30 8″ Hamamatsu PMTs

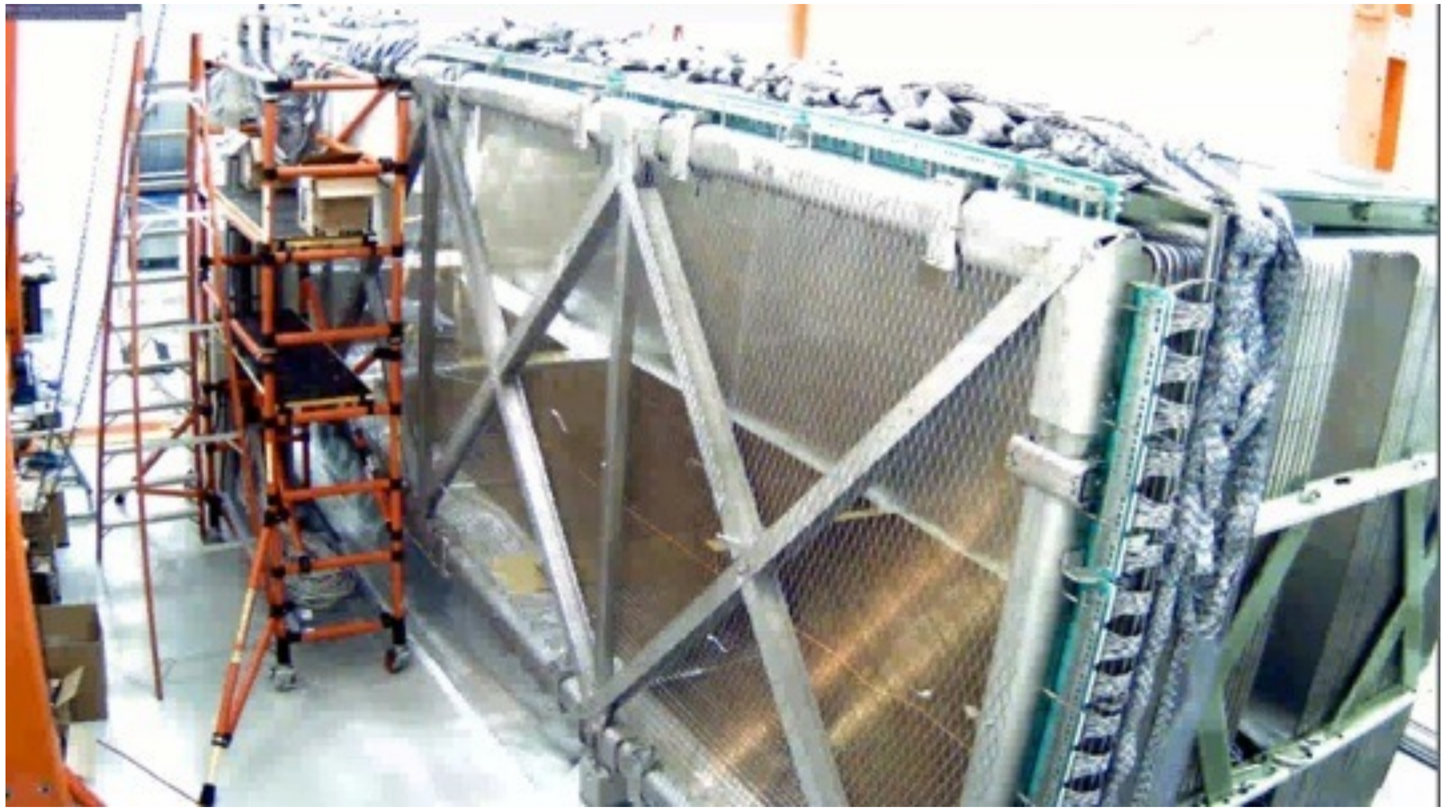


MicroBooNE Experiment

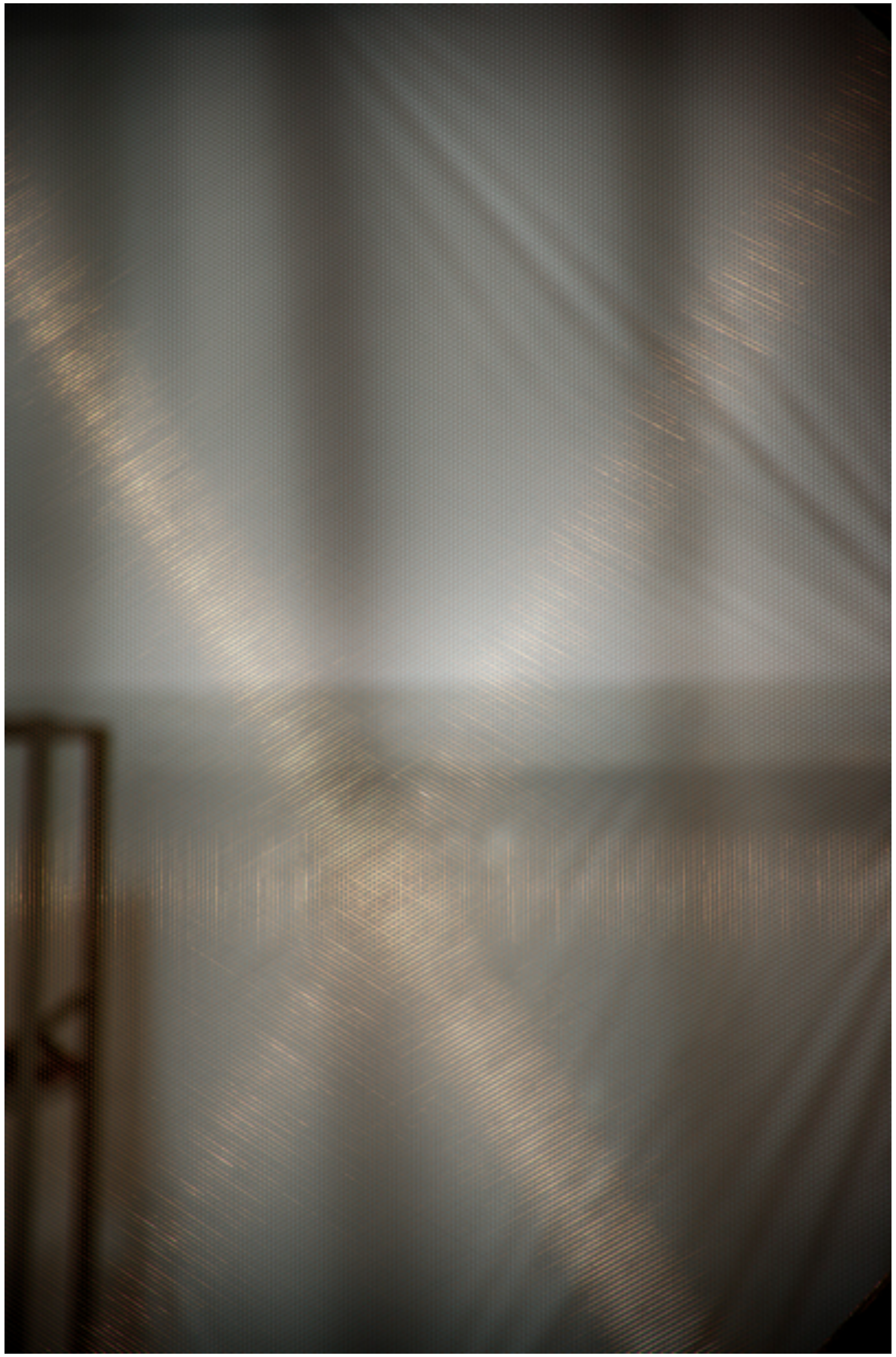
Refs:
1.) *Proposal for a New Experiment Using the Booster and NuMI Neutrino Beamlines*, H. Chen et al., FERMILAB-PROPOSAL-0974

MicroBooNE: TPC Detector

Cryostat Volume	150 Tons
TPC Volume (l x w x h)	89 Tons (10.4m x 2.5m x 2.3m)
# Electronic Channels	8256
Electronics Style (Temp.)	CMOS (87 K)
Wire Pitch (Plane Separation)	3 mm (3mm)
Max. Drift Length (Time)	2.5m (1.5ms)
Wire Properties	0.15mm diameter SS, Cu/Au plated
Light Collection	30 8″ Hamamatsu PMTs

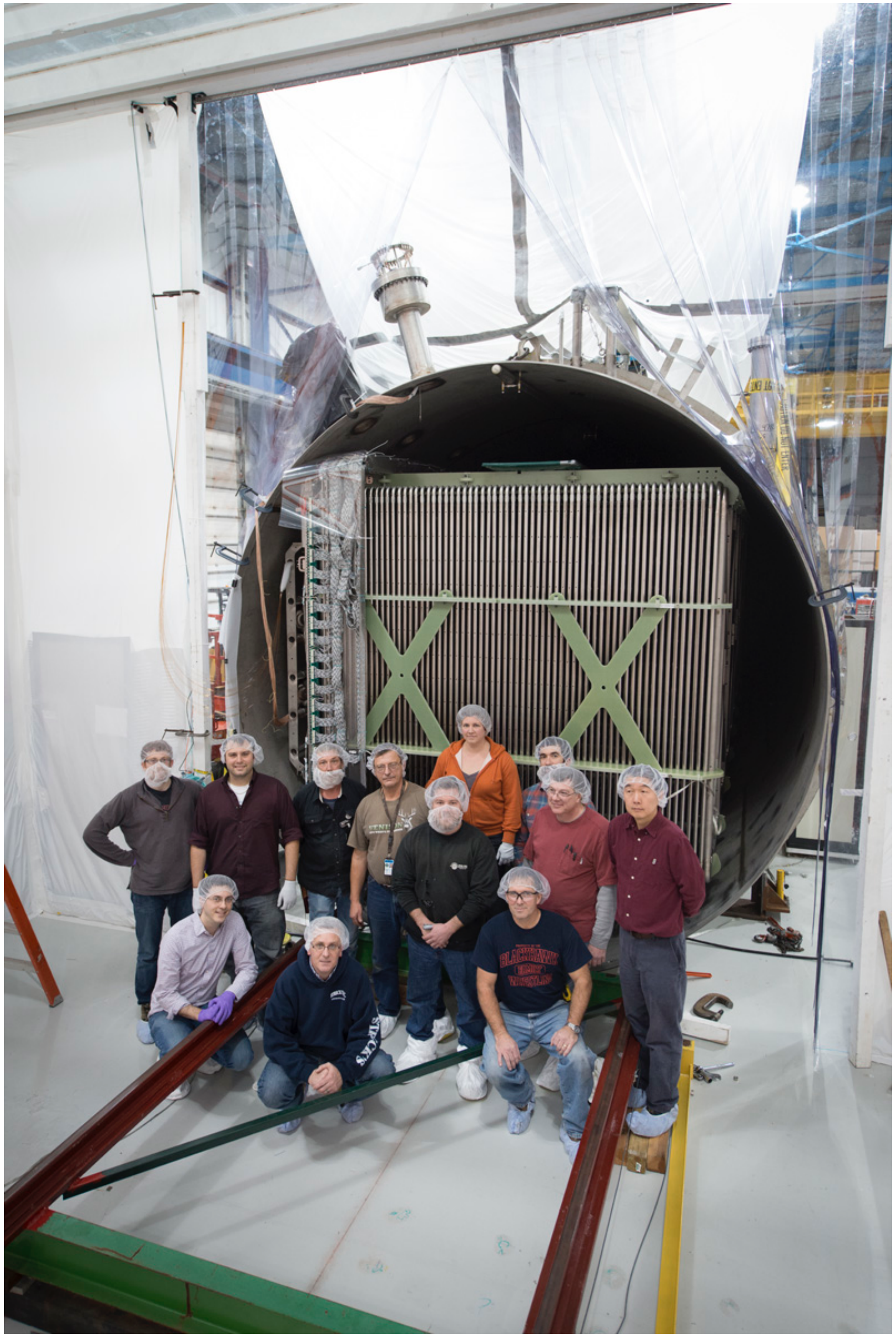


MicroBooNE TPC (Nov. 2013)



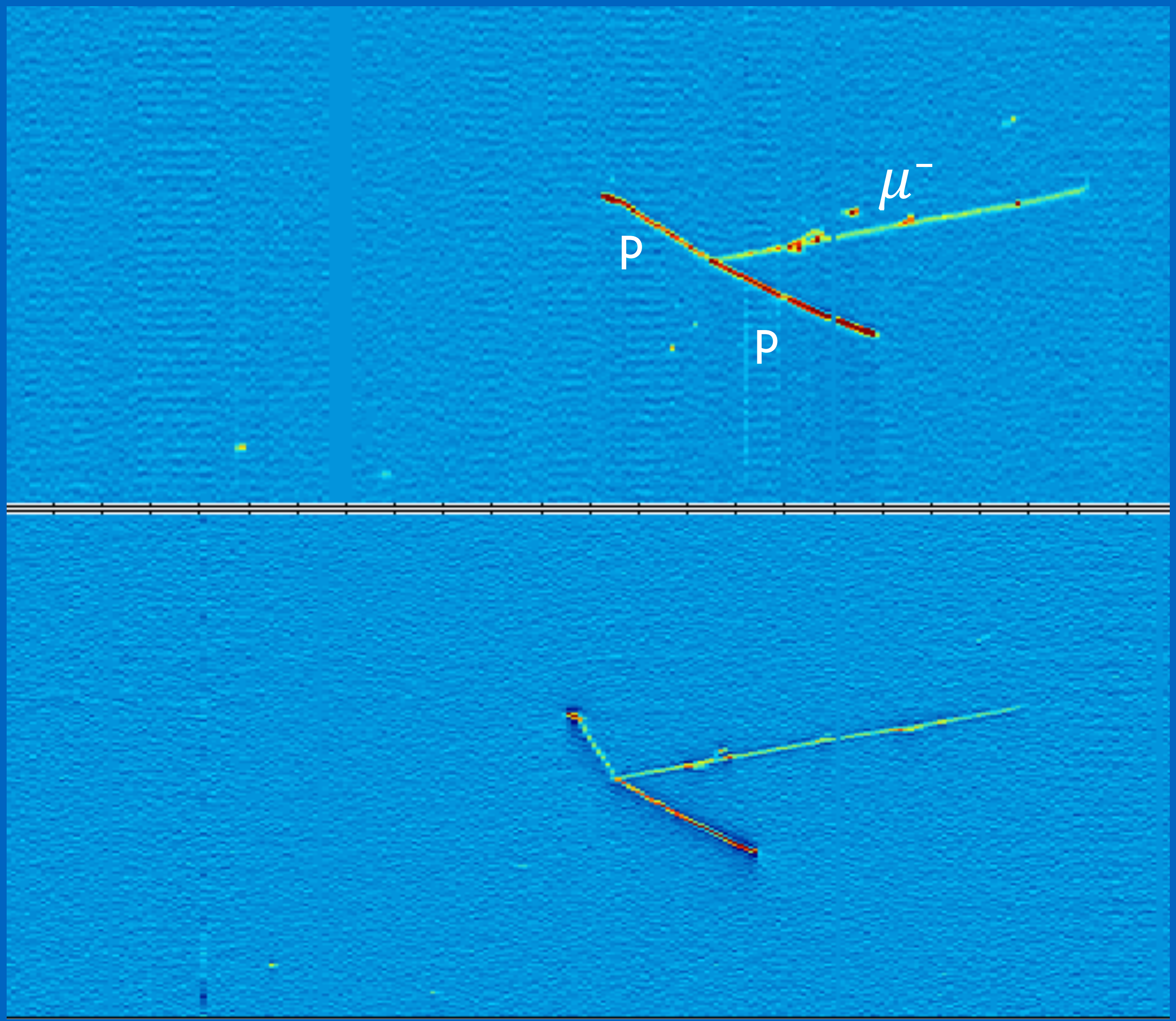
TPC Wires

MicroBooNE Construction



Surprises?

- Looking in two-proton subsample, find events with protons in back-to-back configuration that is a signature of correlated nucleons.
- Statistics are low, but results are suggestive that SRC are active. MicroBooNE can look for this, and will have an even lower proton threshold.



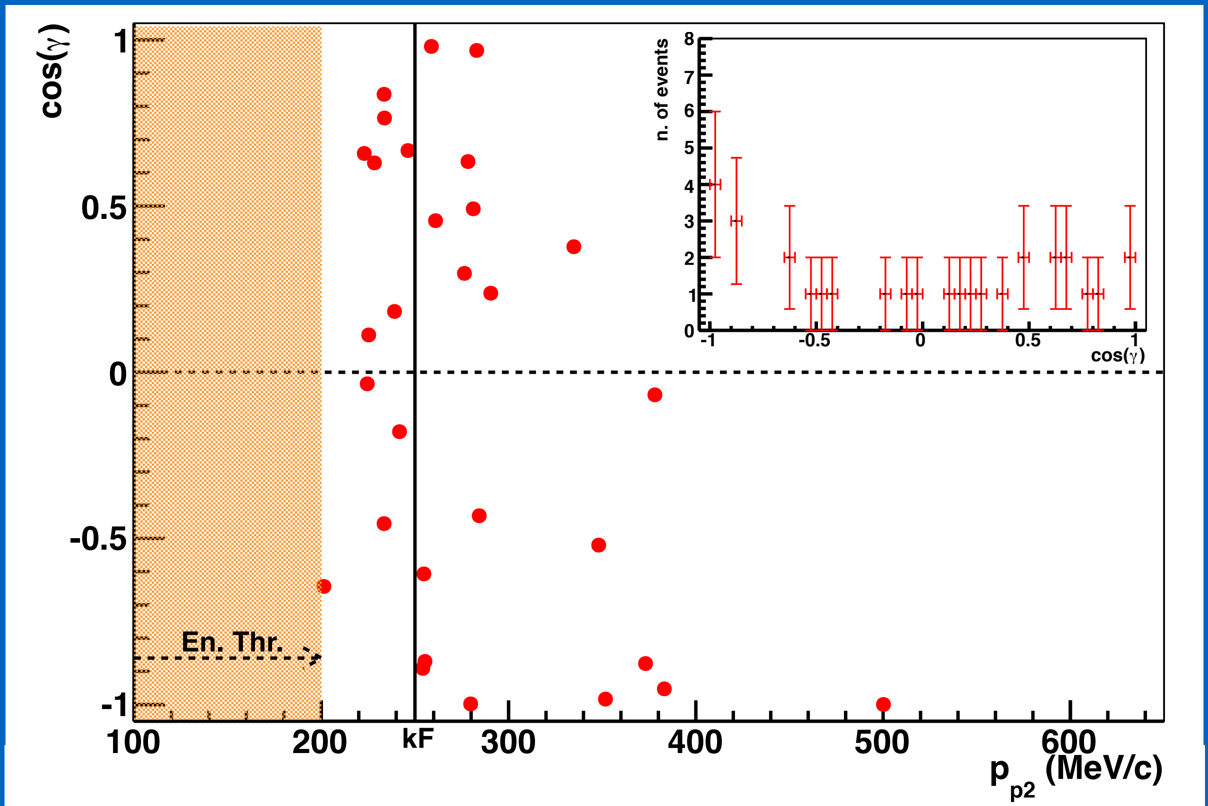
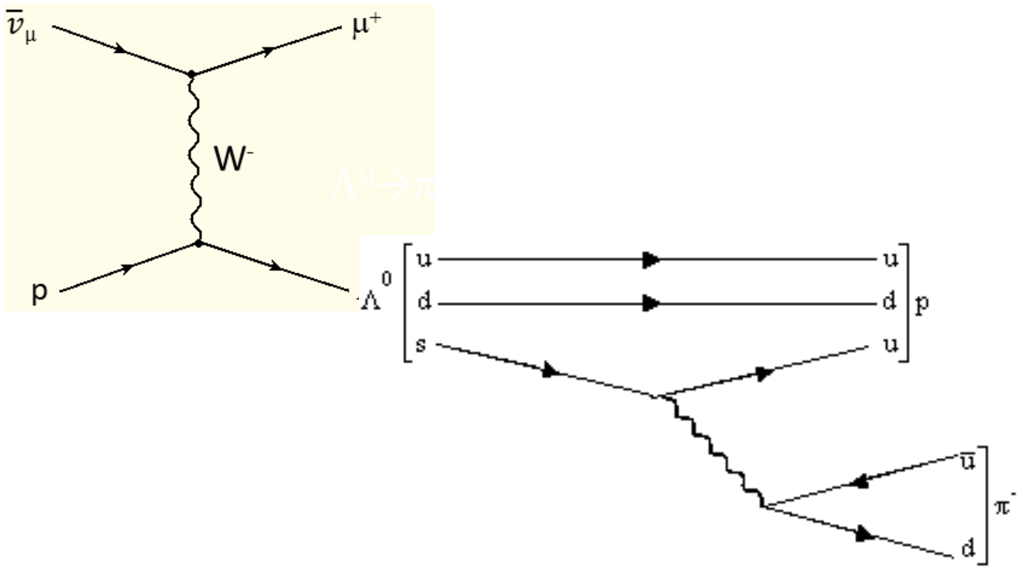


FIG. 2. Cosine of the angle γ between the two protons (Lab frame) vs. the momentum of the least energetic proton in the pair for the 30 events in the $(\mu^- + 2p)$ sample. In the inset is the distribution of $\cos(\gamma)$.

Refs:
1.)*The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT Detector in the NuMI low energy beam line*, R. Acciarri et al, PRD 90 012008 (2014)

ArgoNeuT: Physics

- Excellent resolution allows direct measurement of Hyperon production in neutrino interactions.
- Due to ArgoNeuT's small size, statistics are very limited and containment is a problem, but several candidates are observed.



$\Lambda^0 \rightarrow \pi^+ + p$